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IMPROVING THE PERFORMANCE OF ROADSIDE VEGETATION

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16. Abstract
Vegetation along roadways can be aesthetically pleasing and helps to stabilize the soil, which reduces wind-blown soil and soil erosion. While products containing chloride salts have proven to be very effective in helping to provide safe road surfaces, the accumulation of these products in roadside soils may create conditions unsuitable for the growth of some plant species. The purpose of this study was to determine the impact of a magnesium chloride–based deicer, a sodium chloride-based deicer, and the major salts contained in these deicers on seed germination and seedling growth and development of fifteen species of grasses and forbs native to Colorado. Seven of the fifteen species performed well at the low and medium concentrations of the salts and solutions; these are plants that can likely germinate in roadside areas.

An increase in the concentration of chloride or sodium ions, or both, was related to a greater impact on the proportions of normal and abnormal seeds and seedlings. A few species were more negatively impacted by a particular salt type or formulation. Eight of the fifteen species tested had too few plant counts at either field site or in different soils and treatments to conduct individual data analysis on the impact of salt treatments. Salt treatments had no impact on the average numbers of plants for the remaining seven species, except the two fescue species, which were negatively impacted by high concentrations of salt treatments in topsoil. In general, all species had more plants and greater growth on topsoil than sand, and sand was better than gravel. The salt concentrations in the field plantings were diluted by precipitation during the study so the impacts were probably less than what would be seen with consistently high concentrations.

Implementation:
Using species with the highest germination rate provides the best opportunity for establishing plants along highways treated with deicing products. If possible, planting should be done in the fall and the soil should be amended to promote plant growth. Future studies should quantify conditions of vegetation along highways so that spatial relationships of highway maintenance, site factors, vegetation types, and metrological factors can be assessed.

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EXECUTIVE SUMMARY

Chloride salts are commonly used during the winter months in temperate climates to remove ice and snow from highways. Although these products greatly improve driving conditions, they can have detrimental effects on the vegetation growing along roads and highways. The overall purpose of this study was to determine the impact of a magnesium chloride ($MgCl_2$)-based deicer, a sodium chloride (NaCl)-based deicer, and the major salts contained in these deicers on seed germination and seedling growth and development of fifteen species of grasses and forbs native to Colorado. Based on laboratory seed germination tests, an increase in the concentration of chloride or sodium ions, or both, was related to a greater impact on the proportions of normal and abnormal seeds and seedlings, as well as the proportions of dead and dormant seeds. Species that were least affected by either salt were *Buchloe dactyloides, Bromus marginatus, Elymus trachycaulus, Festuca ovina, Festuca saximontana*, and *Poa secunda*. These top performers attained a rate of > 60% normal germination at 300 and 1350 parts per million (ppm) chloride concentrations of all four salt solutions. A few species were more negatively impacted by a particular salt type or formulation. *Deschampsia caespitosa* and *Koeleria macrantha* were particularly sensitive to both $MgCl_2$ and the $MgCl_2$-based deicer product and less sensitive to NaCl. Proportions of normal *Schizachyrium scoparium* seedlings decreased with increasing concentrations of $MgCl_2$, $MgCl_2$ deicer and NaCl deicer but not pure NaCl. In field plantings, eight of the fifteen species tested had too few plants at either high (2,896 meters) or low (1,524 meters) elevation field sites or in three different soils (sandy topsoil, sand and gravel) and salt treatments (300, 1350, 3000 ppm Chloride) to conduct individual data analysis on salt impacts. Salt treatments had no impact on the average numbers of plants for the remaining seven species ($P < 0.05$)[1], except the two *Festuca* species, which were negatively impacted by high concentrations of salt treatments in topsoil but positively impacted in sand and gravel. Plant counts and biomass were higher at the high elevation site for most of the five species planted at both locations. In general, all species had more plants and greater growth on topsoil than sand and sand was better than gravel.

[1] The **P-value** is the probability of obtaining a test statistic at least as extreme as the one that was actually observed, assuming that the null hypothesis is true

Implementation Statement

The recommendations made within provide information on what species would be best planted at low and high elevations along roads where deicing materials are used. Recommendations are also provided on what studies would be needed to provide a complete planting management system for roadsides impacted by deicing salts.

- Using the species that had the best percent germination for planting in roadside areas such as *Buchloe dactyloides*, *Bromus marginatus*, *Elymus trachycaulus*, *Festuca ovina*, *Festuca saximontana*, and *Poa secunda*, provides the best opportunity for establishing plants along highways treated with deicing products.
- If possible, planting of grasses should be in the fall.
- Soil type had a major impact on total number of plants and biomass index, especially at the high elevation site since more plants grew there than at the low elevation site. Topsoil had the most plants and highest biomass index at both locations. Gravel soil did not provide conditions for many species to germinate and grow. However, a few species such as *Elymus trachycaulus* and *Eriogonum umbellatum* were able to grow on the gravel. Providing a better soil to establish plants in along the highway would promote more plants and better growth of the plants.
- Future studies should focus on quantifying vegetation health along the state highways so that spatial relationships of plant health and highway maintenance, site factors (soils, slopes etc), vegetation types, precipitation and other metrological factors can be assessed. With this field information and our laboratory information management, best management practices (BMPs) can be developed for plantings alongside Colorado highways.
- Since chloride ions are readily removed from the soil, field or greenhouse experiments should be performed in a controlled situation where consistent flushing of soils with known salt solutions is feasible, so a consistent concentration can be provided. After these relationships are established true field testing can be carried out.

The Colorado Department of Transportation (CDOT) can utilize this information, as can various county and city road and bridge departments.

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1.0 INTRODUCTION

Application of chloride salts to roadways for ice removal during the winter months is a general practice throughout the northern and high elevation areas of North America and Europe. Historically, the compound of choice was sodium chloride (NaCl), but magnesium chloride-($MgCl_2$) based products are now being used (Trahan and Peterson, 2007). While products containing chloride salts have proven to be very effective in helping to provide safe road surfaces, the accumulation of these products in roadside soils may create conditions unsuitable for the growth of some plant species. The negative impacts NaCl can have on roadside soils by affecting soil structure, osmotic balance and nutrient availability and stressing or killing vegetation are well documented (Hofstra and Hall 1971, Hall et al. 1972, Piatt and Krause 1974, Viskari and Karenlampi 2000, Norrstrom and Bergstedt 2001, Westing 1984). High levels of salts in the soil can disrupt the osmotic balance in the rhizosphere, making water less available to plants (Hofstra, et al, 1979; White and Broadley, 2001). Elevated levels of salts in the soil can be especially detrimental to woody and herbaceous plants growing in areas that typically receive less than 20 inches of precipitation per year, as well as in areas where rainfall is usually more abundant, but may be experiencing a prolonged period of below normal precipitation (White and Broadley, 2001). Vegetation along roadways is important in that it helps to stabilize the soil, which reduces wind-blown soil and soil erosion, and contributes to the aesthetic appeal along the nation's highways and back roads.

Excessive accumulation of salts, either in the plant tissue or in the soil, can lead to unhealthy grasses and forbs (Environment Canada and Health Canada, 2001). Seeds of salt-sensitive plants may fail to germinate or, if they germinate, the seedlings may die due to the high levels of salt in the soil (Environment Canada and Health Canada 2001, Qian et al 2001). The salt-tolerant species that replace native salt-sensitive species often are not native species, and may alter the surrounding ecosystem (Fischer, 2001). There are many published studies on the tolerance of grass and forb species to NaCl (Camberato et al 2006, Suplick-Ploense et al 2002, Torello and Symington 1984, Greub et al 1985, Alshammary et al 2003). The exact effect of elevated concentrations of salt on a plant species may be difficult to quantify because of the interactions with climate factors. The interactive effects of salinity and temperature can dramatically reduce and delay germination of seed of some grass species. Qian and Suplick (2001) found that the effect of salinity stress on grass germination becomes more pronounced at sub- and supra-optimum temperatures. The authors concluded that the time of seeding can have pronounced effects on germination percentage and rate of seedling growth because of seasonal variations in temperature, as well as the species' response to salinity.

Tolerance of salts by plants varies considerably within and among species, and depends heavily upon the cultural conditions under which a plant is grown (Beaton and Dudley 2004, 2007, Cunningham 2008). Many factors related to previous salt exposure and the plant, soil, water, and the environment interact to influence the salt tolerance of a plant (Beaton and Dudely 2007, Cunningham 2008, DiTommaso 2004).

Few studies have evaluated the impact of $MgCl_2$-based products on plant species planted along roadways. NaCl-based deicers can have harmful effects on roadside vegetation, but additional studies are needed to compare plant species response to both NaCl-based deicers and $MgCl_2$-based deicers (Trahan and Peterson, 2005). Thus the overall purpose of this study is to determine the impact of a $MgCl_2$-based deicer, a NaCl-based deicer, and the major salts contained in these deicers, on the germination and viability of seeds of several species of grasses and forbs native to Colorado, as well as to determine the impact that these $MgCl_2$-based and NaCl-based deicers have on seedling growth and development. The knowledge gained from this study can be used in roadside revegetation guidelines used by federal, state, and local departments of transportation. The research objectives were to: 1) Determine the effects of a $MgCl_2$-based deicer, a NaCl-based deicer, and the major salts contained in these deicers, on seed germination and viability under controlled conditions of 15 species of native grasses and forbs used for roadside revegetation; and 2) determine the effects of elevation, soil type and $MgCl_2$ and NaCl on seed germination, seedling survival and growth of 15 species of grasses and forbs under field conditions.

2.0 METHODS

2.1 Roadside Soil Sampling

In order to determine the appropriate concentrations of NaCl and $MgCl_2$ solutions to use in this study, soil was sampled in late May 2008 along Interstate 70 (I-70), Georgetown to west of Vail Pass, Colorado (CO). The late May collection provided us with soil conditions similar to when seeding would take place along our highways. Twelve randomly selected areas were sampled from 100-meter sections of roadside that fit one of three types of roadside slopes: 1) level, 2) upslope, or 3) downslope. Four sections of each of the three roadside types were sampled. At any site where a roadside ditch did not occur, samples were collected along the 100 meter transect at three distances (0, 1, or 2 meters) away from the beginning of the vegetation along the roadside. At two sites where roadside ditches occurred, soil samples were collected along the 100 meter transect at the foreslope, ditch and backslope areas of the roadside, which were not at set distances. Soil samples, 5 centimeters (cm) deep, were collected every 10 meter along the 100 meter transect of each distance or topographic zone and homogenized in a single mixed sample.

Soil samples were air-dried for 72 hours, sieved to 2 millimeters (mm) to exclude organic matter and rocks and chemically analyzed by AgSource Harris Laboratories in Lincoln, Nebraska (NE). Samples were analyzed for electrical conductivity (EC) and soluble salts using saturation paste methods, pH, percent organic matter, total nitrogen, phosphorus (Bray 1 test), potassium (K), calcium (Ca), sodium (Na), magnesium (Mg), sulfur, zinc, manganese, copper, iron, boron, boric acid, and chloride. Sodium absorption ratio (SAR) was calculated and cation exchange capacity (CEC) was estimated by measuring the amount (milliequivalents per liter [meq/L]) of base cations K^+, Mg^{+2}, Ca^{+2}, Na^+ and H^+ in the soil.

We found the ion concentrations much lower than expected even though we sampled fairly soon after snow melt. The chloride concentration ranged from 17 to 324 ppm and sodium concentrations ranged from 14 to 223 ppm. These ranges are not unlike those found in January and May along roads in the Lake Tahoe area of California (Munck et al 2010) where they found high concentrations in foliage and considerable tree mortality. We found soil concentrations along roads treated with $MgCl_2$ in the summer for dust control to have higher soil concentrations of chloride (Goodrich et al 2009). The general hypothesis about vegetation damage and soil concentrations is that since the ions are very mobile they are rapidly moved downward in the soil. Plants will take up large amounts of the ions and suffer damage even as the ions are moved out of the upper soil layers during precipitation events. Foliar concentrations of toxic ions like chloride are the most reliable method for assessing ion impacts on at least woody plants. See Table one for the concentrations found along I-70.

Table 1. Salt ion concentrations[x] along I-70 (Georgetown to Vail Pass, CO) May 2008.

Mile marker[y]	Slope Type	Distance[z]	Ditch Topography	Cl^- (ppm)	Na^+ (ppm)	Mg^{+2} (ppm)
198	level	0m	-	52	106	92
		1m		73	99	108
		2m		151	128	112
192	downslope	0m	-	73	137	69
		1m		52	90	94
		2m		42	67	81
200.5	level	0m	-	115	88	155
		1m		46	64	135
		2m		25	85	139
205	downslope	0m	-	158	149	279
		1m		140	79	225
		2m		185	73	261
189	upslope	0m	-	25	75	128
		1m		20	39	142
		2m		21	39	109
188	upslope	0m	-	25	53	110
		1m		17	30	118
		2m		18	41	125
176	downslope	0m	-	105	28	330
		1m		62	23	309
		2m		31	21	336
200	level	0m	-	276	196	142
		1m		287	185	145
		2m		223	193	216
195	level	0m	-	324	223	59
		1m		195	161	72
		2m		247	189	101
193	upslope	1m	foreslope	63	89	94
		4m	ditch	237	144	89
		6.5m	backslope	19	26	114
221	downslope	0m	-	18	68	133
		1m		69	72	161
		2m		26	58	155
217	upslope	0.8m	foreslope	145	69	165
		3m	ditch	36	20	137
		8.5m	backslope	34	14	138

[x] Concentrations = based on one sample from mixed collection of 10 subsamples per distance from road

Cl= chloride, Na = sodium and Mg= magnesium

[y] = "Milemarker" refers to nearest mile marker to sample location, along I-70 in Colorado.

[z] = "Distance" refers to the distance from the vegetation edge along the highway.

2.2 Laboratory Germination Trials

We determined the effects of two salt solutions and two deicer solutions on the germination viability of fifteen native grasses and forbs obtained from Pawnee Buttes Seed Company in Fort Collins, CO) in a set of laboratory experiments in 2009. The germination testing was conducted according to protocol of the Association of Official Seed Analysts (AOSA) (http://www.aosaseed.com/). For more details on these methods please see Appendix Table A- 3.

Seed used in the germination study was first cleaned at the Colorado Seed Laboratory. Seed was cleaned of chaff and debris in a seed blower and remaining debris were removed by microscopic examination. The seed was either considered 'pure' (as was the case with *Linum lewisii*, *Penstemon strictus,* and *Bromus marginatus*), or required further examination. If the seed required further analysis, seeds were either assessed with forceps (*Schizachyrium scoparium)*, or microscope (*Elymus trachycaulus*) to determine the presence of a caryopsis (grain or fruit).

Germination trials used growth chambers, with a light source and diurnal temperature fluctuations. For all species and treatments, seeds were subjected to optimal growing temperatures and standard assessment procedures based on AOSA standards. For each repetition of every treatment, seeds were placed in a plastic translucent box on a sheet of 38-lb brown germination paper obtained from Anchor Paper Company in St Paul, Minnesota. Depending on the treatment, the germination paper was soaked with: distilled water (control), Apex® (a magnesium chloride-based deicer solution), Ice Slicer® (a sodium chloride-based deicer solution), sodium chloride (NaCl), or magnesium chloride hexahydrate ($MgCl_2 * 6\ H_2O$). For the two deicer solutions and the two salts, three solutions were prepared based on chloride concentrations of 300, 1350, and 3000 ppm. The low concentration was selected based on the highest values found along I-70 and the two high concentrations were selected based on previous studies at Colorado State University along non paved roads that were treated with $MgCl_2$ for dust treatment (Goodrich et al. 2009). For each species there were 100 seeds per replication, with 4 replications, 6 salt solutions, 6 deicer solutions, and 1 control solution, for a total of 6,800 seeds. All seeds were dry cold stratified (pretreating seeds at 38 F to simulate natural winter conditions) for 30 days prior to germination tests. Germination was assessed initially at day 5, 6, 7, or 10 (depending on species). Seeds were considered to be undergoing normal germination if both a root radical and a young stems were present. A second assessment was conducted at day 14, 16, 21, or 28 (depending on species). A third assessment was carried out and non-germinating seeds were assessed for viability by tetrazolium tests (a stain that detects living cells).

2.3 Field Study

2.3.1 Field Study Sites

A low elevation (1,524 meters; 5,000 feet [ft]) and a high elevation (2,896 meters; 9,500 ft) field site were established to represent the elevation-mediated conditions along Colorado's highways. The low elevation site was at Colorado State University's Agricultural Research and Education Center (104°59'50.118" W 40°39'22.612"N) near Fort Collins, CO, with wind breaks on all sides of the site. The high elevation site was located near the Gilpin County Judiciary Office and Dory Hill Cemetery, north of Blackhawk, CO, (105°29'6.078"W 39°51'18.701"N) with a wind break of aspen forest 5 meters from the west and east sides of the site.

2.3.2 Planters

At each study site, twenty-one wooden oriented strand board (OSB) planters (2.4 meters by 1.2 meters by 0.4 meters; 8 ft. by 4 ft. by 1.3 ft.) were constructed. The bases of all planters were covered with aluminum fly screen and the tops covered with 6 mm mesh wire screen to restrict animal predation of the seeds or seedlings. Each planter was divided into three sub-compartments (2.6 ft. by 4 ft.), by OSB dividers, and each of these was filled to a depth of 30 cm (12 inches [in]) with one of three soil types: clay soil (top soil, organic material, sand), sandy soil (20% topsoil, 80% sand), and decomposed rock soil (gravel end run material), hereafter, referred to as topsoil, sand, and gravel, respectively. See Table 2 for details on composition of the soils. Soils were obtained from a local soil supply company that used local topsoil, decomposed organic material and washed sands, and gravel end run material to make the topsoil, sand, and gravel soils, respectively. The three soils were assigned to the same sub-compartment in each planter.

Table 2. Soils used in field planters at low and high elevation sites, Fort Collins and Black Hawk, CO, 2008-2009.

Type	Debris (%)	Sand (%)	Silt (%)	Clay (%)	Org %	N (ppm)	P (ppm)	K (ppm)	pH	Sol salts (mmhos/cm)	CEC	Na (ppm)	Mg (ppm)
Clay topsoil	34	59	23	18	2.3	193	163	502	7.6	1.31	21.3	121	271
Sandy soil	30	87	11	2	0.8	53	42	164	8.0	0.5	13.7	48	128
Gravel	45	91	1	8	0.3	2	5	35	7.9	0.14	3.0	13	73

Debris= rocks and particles removed by a 2 mm screen, Org= percent organic material, N= parts per million of nitrogen, P= parts per million of phosphorus, K= parts per million of potassium, pH = acidity measure of the soil, sol salts= soluble salts, CEC= cation exchange capacity, Na= sodium in parts per million and Mg= magnesium in parts per million.

2.3.3 Salt Treatments

The two salts used in our studies were sodium chloride (NaCl) and magnesium chloride hexahydrate ($MgCl_2$ * 6 H_2O). Three concentrations of each salt were prepared, such that chloride was at 300, 1,350 or 3,000 ppm. At each location, three planters were randomly selected for the 'control' treatment, and were drenched with water until the entire soil profile was saturated. Each of the six salt solutions was randomly assigned to three planters. Pre-measured amounts of NaCl or $MgCl_2$ were added to a 1,135 liter (300 gallon [gal]) holding tank and applied using a transfer pump and hose. A total of 1,135 liters (300 gal) of each solution was applied to each planter, and the soil was mixed to ensure uniform saturation. Treatments were applied on October 18th and 19th, 2008 at the Black Hawk study site and November 7th and 12th, 2008 at the Fort Collins, low elevation site. Planters were allowed to drain 3-7 days and then seeds were planted in a randomly selected half of each soil compartment. On March 22 & April 19, 2009, we applied 378 liters (100 gal) of the appropriate salt solution to all planters at both sites. The remaining half of each compartment that was not planted in the fall of 2008 was planted with the same 10 species in the same manner. See Appendix Tables A-1 and A-2 for more details.

2.3.4 Planting

The same 15 native plant species evaluated in the germination tests were evaluated in the field. Five species that would normally be planted in cooler and wetter roadsides were selected as high elevation species and were planted only at the high elevation site. Five species that would normally be planted in warmer drier sites were designated as low elevation species and were planted at the low elevation site. Five more species were planted at both sites for a total of 10 species at each site. One half of each compartment (soil type) was randomly selected and planted in fall of 2008 (Oct 25, 2008 at high elevation site , November 14 2008 at low elevation sit), and the other half was planted in spring 2009 (April 19, 2009 at high elevation site, April 12, 2009 at low elevation site). A movable wooden grid was used to plant the seeds of each species in a randomly selected (20 by 24 cm, 8 by 9.6 in) compartment. Seeds were stored dry at 5 degrees Celsius (°C) for at least four weeks prior to planting. In order to attain approximately 50 germinating seeds per grid square, Percent Live Seed (PLS) (seed purity * germination rate = PLS) was calculated for each species and the number of seeds planted was adjusted accordingly. The average weight of the PLS-adjusted seed counts was used to prepare seed amounts for each compartment. See Table 3 for details on seed counts and purity. A small amount of washed sand was added to a shaker jar with a perforated lid and the seed and sand mixture was shaken onto the compartment. When all ten species were planted, a straw landscaping mat (19 mm; ¾ in thick), which consisted of double net straw (70%) and coconut (30%) (Bionet©, Evansville, IN), was placed on the soil surface. Landscaping mats are commonly used after seeding along Colorado’s highways. Planters were then covered with wire mesh (6 mm; ¼ in) covers to deter rodents. Monthly total precipitation values were obtained from NOAA meteorological stations near the field sites. See Appendix Table A-4 for more details.

Table 3. Seed germination, purity and weight of species planted at the low and high elevation field sites, Fort Collins and Black Hawk, CO, 2008-2009.

Species	Germ rate[y]	Purity[x]	PLS[v]	Actual # seeds[u]	Weight 1[t]	Weight 2	Weight 3	Average[s]
Black Hawk								
Deschampsia caespitosa	0.93	1.00	0.93	54	0.01	0.01	0.01	0.01
Festuca ovina "Covar"	0.93	0.98	0.91	55	0.04	0.04	0.04	0.04
Festuca saximontana	0.96	1.00	0.96	52	0.04	0.03	0.03	0.03
Bromus marginatus "Bromar"	0.98	1.00	0.98	51	0.37	0.37	0.39	0.38
Poa alpina	0.90	0.94	0.85	59	0.03	0.03	0.03	0.03
Fort Collins								
Buchloe dactyloides	0.97	1.00	0.97	52	0.78	0.78	0.87	0.81
Bouteloua gracilis	0.86	0.77	0.66	76	0.05	0.06	0.05	0.05
Koeleria macrantha	0.78	0.86	0.67	75	0.02	0.02	0.02	0.02
Poa secunda	0.86	0.98	0.85	59	0.03	0.03	0.03	0.03
Bouteloua curtipendula	0.72	0.99	0.72	70	0.27	0.25	0.28	0.27
Both sites								
Elymus trachycaulus	0.82	0.98	0.80	63	0.25	0.27	0.23	0.25
Schizachyrium scoparium "Pastura"	0.70	0.51	0.36	140	0.29	0.26	0.27	0.27
Linum lewisii (Linum perenne var. Lewisii)	0.93	0.99	0.92	54	0.15	0.12	0.12	0.13
Penstemon strictus	0.86	0.99	0.85	59	0.15	0.05	0.05	0.05
Eriogonum umbellatum	0.64	0.92	0.59	85	0.29	0.29	0.31	0.30

[z] Code: unique to each species; uses first two letters from the genus and species

[y, x] Values provided by the Pawnee Buttes Seed Company (Fort Collins, CO)

[v] Percent Live Seed (PLS): calculated by multiplying the given germination rate and purity of seed used

[u] The actual number of seeds refers to the number of seeds planted per grid square. This was calculated by multiplying the number germinating seedlings desired per grid square (50) by the PLS for each species.

[t] Weights: The mass of the actual number of seeds, in grams. Mass was the average wt of 3 replicates of 50 seeds.

[s] Average: the average mass (in grams) of the actual number of seeds.

2.3.5 *Soil Samples*

Soil samples were collected from all planters after the application of spring salt solutions, and the second set were collected during the second growth assessment (August 20 and 21). One composite soil sample was collected from the top 5 cm (2 in) of soil from each sub-compartment for a total of 63 samples per field location. Samples were air dried and sifted using a 6 mm screen to remove pebbles and large pieces of organic matter. The processed samples were sent to AgSource Harris Laboratory (Lincoln, NE) for chemical analysis. See Tables 4 and 5 for the soil analysis data.

Table 4. Chemical analysis of soils in 2009 growing season, low elevation site, Fort Collins, CO.

Salt Treatment	Chloride Concentration	Soil Type	Cl^-, ppm		Na^+, ppm		Mg^{+2}, ppm	
			Spring 09	Fall 09	Spring 09	Fall 09	Spring 09	Fall 09
NaCl	300	Gravel	49	2	105	16	244	84
		Sand	35	2	107	21	112	116
		Topsoil	42	4	193	70	261	305
NaCl	1350	Gravel	378	3	622	36	438	66
		Sand	69	2	320	30	73	116
		Topsoil	135	8	456	249	171	282
NaCl	3000	Gravel	171	2	356	55	280	64
		Sand	250	3	605	98	62	90
		Topsoil	336	35	956	520	164	246
$MgCl_2$	300	Gravel	365	3	666	19	319	165
		Sand	67	6	36	19	284	185
		Topsoil	129	35	94	60	373	383
$MgCl_2$	1350	Gravel	169	7	30	23	378	237
		Sand	209	22	43	23	440	221
		Topsoil	380	19	93	46	878	570
$MgCl_2$	3000	Gravel	258	3	70	19	690	224
		Sand	268	36	258	26	355	277
		Topsoil	427	102	341	58	522	645
Control	-	Gravel	203	2	413	24	374	90
		Sand	7	2	35	14	92	128
		Topsoil	27	5	55	58	150	321

[z] One replicate inadvertently received NaCl 3000 ppm treatment in spring treatment.

Table 5. Chemical analysis of soils in the 2009 growing season, high elevation site, Black Hawk, CO.

Salt Treatment	Chloride Concentration	Soil Type	Cl^-, ppm		Na^+, ppm		Mg^{+2}, ppm	
			Spring 09	Fall 09	Spring 09	Fall 09	Spring 09	Fall 09
NaCl	300	Gravel	22	8	30	16	104	84
		Sand	28	7	37	14	143	122
		Topsoil	36	13	105	70	351	324
NaCl	1350	Gravel	82	8	153	45	82	91
		Sand	63	12	121	45	140	118
		Topsoil	94	15	188	127	349	298
NaCl	3000	Gravel	108	11	273	67	64	77
		Sand	129	9	334	60	114	104
		Topsoil	123	27	645	457	323	303
$MgCl_2$	300	Gravel	28	6	13	13	164	124
		Sand	34	6	14	15	213	165
		Topsoil	62	12	33	29	522	454
$MgCl_2$	1350	Gravel	78	6	12	17	311	228
		Sand	83	6	16	14	383	214
		Topsoil	120	11	48	30	660	555
$MgCl_2$	3000	Gravel	105	7	10	14	317	246
		Sand	139	7	19	14	512	291
		Topsoil	133	16	34	35	1149	572
Control	-	Gravel	3	8	6	12	85	93
		Sand	4	6	18	15	146	133
		Topsoil	6	14	31.7	37	312.7	325

2.3.6 Growth Assessments

The spring- and fall-sown subplots were evaluated for seed germination and seedling growth twice during the summer (July 15 and 16 and August 20 and 21, 2009). During each assessment, all live seedlings were tallied, and heights recorded on three randomly selected seedlings. Biomass index was calculated as the product of the average seedling height and the seedling count for each species. Seedling emergence started at both elevations after June 20, 2009. All planters were weeded every two weeks from June 15 to August 21, 2009.

2.4 Statistical Analysis

All statistical analyses were conducted using SAS© 9.2 statistical software (SAS Institute, Inc., Cary, N.C., USA). Germination trial data were analyzed using the 'proc glimmix' procedure in SAS. A separate analysis was run for each of the four possible seedling outcomes (i.e., normal, abnormal, dormant, or dead). Each analysis used a series of 'estimate' statements to compare eight pairs of treatment groups, including the control group vs. each of the high concentrations, and the high vs. the low concentrations of each solution (e.g., control vs. $MgCl_2$ high, $MgCl_2$ high vs. $MgCl_2$ low).

Field data were analyzed as a split-plot randomized complete block design using the 'proc mixed' program in SAS analysis of variance (ANOVA) with repeated measures. Salt treatments were considered 'whole plot' variables, soil type was analyzed as a split plot variable, and planting date was considered a repeated measure, as it occurred twice. The response variables used included: the logarithm base 10 (log_{10}-) transformed average number of plants per grid square; the log_{10}- transformed average plant height; or the log_{10}- transformed average biomass index. Biomass index was calculated species-wise by multiplying the average number of individuals by the average height. The log_{10}- transformation was used because initial analyses indicated that counts and heights were broadly distributed. The mathematical model used to describe the relationship between variables was determined using the 'glm select' program in SAS, which allows the user to include continuous variables in the selection process. A forward selection method was utilized, and those variables with the greatest Schwarz-Bayesian Information Criteria (SBC) scores were included in the final model. Contrast statements were added to detect linear responses to each of the salt treatments and define what variables will be compared.   The following contrast statements were used to test for linear trends for each of the two salt treatments: "contrast 'Mg Linear' treatment, 1, -1, 3, 0, 0, 0, -3; " "contrast ,'Na, Linear', treatment,0, 0, 0, 1, -1, 3, -3;" which correspond to the seven treatments: MgCl1350, MgCl300, MgCl3000, NaCl1350, NaCl300, NaCl3000, NaClMgCl0.

3.0 RESULTS

3.1 Laboratory Germination Trials

The proportion of abnormal and dead and dormant seedlings increased with increasing concentrations of chloride and/or sodium ions for most species. Some species showed little to no seed dormancy, while the proportion of dormant seeds increased with ion concentration for others. A few species showed increased numbers of dead seeds with increasing ion concentration. Delays in germination were observed for some species.

Some species were more or less affected by one or both salt types than others. Species were identified as being more or less affected by salt treatment by comparing the proportion of normal seedlings in the control group to those in the various treated groups (Figures 1 through 15). Those species that were least affected by salt (regardless of type) include *Buchloe dactyloides*, *Bromus marginatus*, *Elymus trachycaulus*, *Festuca ovina*, *Festuca saximontana*, and *Poa secunda*. These top performers attained a rate of at least 60% normal germination under the low and medium concentrations of all four salt solutions. The species most affected by low to high salt concentrations included *Bouteloua gracilis, Deschampsia caespitosa*, *Festuca ovina*, *Koeleria macrantha*, *Linum lewisii*, *Penstemon strictus*, *Poa alpina* and *Poa secunda.*

A few species were more impacted by a particular salt type or formulation than the other treatments. *Deschampsia caespitosa* and *Koeleria macrantha* were particularly sensitive to both $MgCl_2$ and the magnesium-based deicer product and less sensitive to NaCl (Figures 5 and 10). The presence of Na^+ was more detrimental than $MgCl_2$ at the same concentration of Cl^- for several species such as *Elymus trachycaulus* and *Linum lewisii* (Figures 6 and 11). In contrast, proportions of normal *Schizachyrium scoparium* seedlings decreased with increasing concentrations of $MgCl_2$, $MgCl_2$ deicer and NaCl deicer, but not pure NaCl (Figure 15). The deicer products negatively impacted the proportion of normal seedlings for species such as *Linum lewisii*, and high concentrations of both the magnesium and sodium-based deicer products had strongly negative impacts on the germination of *Festuca saximontana* (Figures 9 and 11). Finally, although it was among the best performing species we tested, *Elymus trachycaulus* was clearly affected by the high concentrations of both sodium-based treatments and the magnesium-based deicer product (Figure 6). There were no major differences in the performance of the five species selected to represent plants normally planted at high and low elevations.

3.2 Specific Species Germination

Bouteloua curtipendula (sideoats grama): The proportion of normal seedlings was 40% or lower for most treatments. Although there were significant differences in the proportions of dead and dormant seedlings, the differences were not operationally important since the germination rate was low overall (Figure 1). High numbers of dead seeds occurred, regardless of treatment or concentration. Under control conditions, most (85%) normal seeds germinated by the first assessment. This basic pattern persisted throughout all treatments and concentrations, (except for the low concentration of NaCl, where nearly equal numbers of seeds germinated by assessments one and two), although a much greater proportion of seeds germinated by the first assessment compared to the second.

Bouteloua gracilis (blue grama): The growth response of *B. gracilis* was a clear example of two of the major trends seen among species in the germination study; as salt concentrations increased, the proportion of normally-germinating seeds decreased, and the proportion of abnormal seedlings increased (Figure 2). The proportion of dead seeds increased as the concentration of NaCl increased, but there was no discernable pattern among the other salt treatments. There were no dormant seeds or delay in germination.

Bromus marginatus (mountain brome): Overall germination of mountain brome was very good (Figure 3). This grass was most affected by the deicing products compared to the pure salts, especially the sodium-based deicer product. The proportion of dead seeds increased with solution concentration, and was highest in the high concentrations of both deicer products and NaCl. The proportions of abnormal seedlings were low among all treatments, except for the high concentration magnesium-based deicer product. There were no dormant seeds.

Buchloe dactyloides (buffalo grass): The proportions of normal seedlings did not differ between the control and the low concentrations of any of the four salt treatments (Figure 4). The highest concentration of the magnesium chloride-based deicer product (Apex®) induced more abnormal growth. The number of dead seeds trended upward with increase in concentration of the two salts and the $MgCl_2$ and the NaCl-based deicer products. The proportion of dormant seeds clearly increased with increases in concentration for all four salt treatments. Under control conditions, most seeds germinated by the first assessment. This pattern was similar for most treatments and concentrations, except for the low concentrations of all four treatments. Under these conditions, overall germination was comparably low, with similar numbers of germinating seeds at each assessment.

Deschampsia caespitosa (tufted hairgrass): This species showed no difference among the proportions of normally-germinating seeds and the control at the low concentrations of any of the four salt treatments (Figure 5). *D. caespitosa* appears to be particularly sensitive to $MgCl_2$ (both the pure salt and the deicer product), as the proportion of abnormal seedlings was very high in comparison with all three concentrations of NaCl and two of the concentrations of NaCl-based deicer product. The proportion of dead seeds was greater than the control at the highest concentration of three of the salt treatments ($MgCl_2$-based deicer, NaCl, and the NaCl-based deicer). There were no dormant seeds detected for this species and under control conditions, most seeds germinated by the first assessment. This pattern was similar for most treatments and concentrations, except for the high concentrations of the two magnesium-based treatments and the sodium deicer product, where there were low germination rates.

Elymus trachycaulus (slender wheatgrass): Overall, *E. trachycaulus* performed very well in this study; only the highest concentrations of the two deicing products and NaCl caused lower proportion of normal seedlings, relative to the control (Figure 6). Again, the proportion of abnormal seedlings trended upward with increase in salt concentrations, and was the greatest among the highest concentrations of both deicing products and NaCl. The proportion of dead seeds also increased with chloride concentration, and was greatest (>50%) at the highest concentration of sodium-based deicer. There were no detected dormant seeds for this species. Under control conditions, most seeds germinated by the first and second assessments. Seeds exposed to the low concentrations of $MgCl_2$ and NaCl germinated at rates similar to the control.

Eriogonum umbellatum (sulfur flower buckwheat): *E. umbellatum* did not germinate in this study, regardless of treatment (Figure 7). Dormant seeds made up the vast majority of the non-germinated seed. Proportions of dormant seed increased with concentrations of the two basic salts (NaCl and $MgCl_2$), and decreased with increasing concentrations of the two deicer products.

Festuca ovina (sheep fescue): Overall, germination rates were high for this species. Proportions of normally-germinating seeds were similar between the control and the low concentrations of each of the four salt treatments (Figure 8). The proportion of abnormal seedlings was very high (>60%) among the high concentrations of three of the four salt solutions. Again, the proportion of abnormal seedlings trended upward with salt concentration. The proportion of dead seeds did not follow any particular trend, except among the three concentrations of sodium-based deicer product; here the number of dead seeds clearly increased from the low to the high concentration. Under control conditions, most seeds germinated by the first assessment. This pattern was similar for the low and medium concentrations for most treatments, except the medium concentration of the sodium deicer, which showed similar proportions of germinating seeds for the first and second assessments. Seeds exposed to the high-concentration solutions germinated later, usually by the second assessment.

Festuca saximontana (Rocky Mountain fescue): *F. saximontana* showed no significant difference among the proportions of normal seedlings between the control and the low concentrations of any of the four salt treatments (Figure 9). The proportion of abnormal seedlings was high (nearly 70%) among the high concentrations of three of the four salt solutions. *F. saximontana* had high proportions of abnormal seedlings when exposed to the high concentrations of both deicer products and NaCl. Under control conditions, most seeds germinated by the second and third assessments. There were no other treatments or concentrations that showed a similar pattern and most treatment-concentration combination resulted in different proportions of germinating seeds for each assessment.

Koeleria macrantha (prairie junegrass): Normal germination under control conditions was high for *K. macrantha* (>90%), and did not differ for the low concentrations of any of the four salt treatments (Figure 10). Proportions of abnormal seedlings ranged from 42-68% among medium and high concentrations for three of the four salts (high concentration of sodium-based deicer was 21%). Numbers of dead seeds trended upwards with increasing salt concentrations, and this was especially evident for the high concentration sodium-based deicer (>40%). Dormant seeds were not detected for this species. Under control conditions, most seeds germinated by the second assessment. This pattern was similar for the low and medium concentrations for most treatments, except for the seeds treated with the medium concentration $MgCl_2$, which had very low germination rates. The high concentration for all treatments generally resulted in delayed germination (i.e., germination occurred by the second and third assessments), or germination was too low to identify a pattern.

Linum lewisii (Lewis flax): Similar to *F. ovina* and others, this species showed no difference among the proportions of normal seedlings between the control and the low concentrations of any of the four salt treatments (Figure 11). Proportions of normal seedlings decreased with ion concentration for three of the four salt treatments, including the two deicer products and NaCl. The proportion of abnormal seedlings increased with increased concentrations for these same three salt treatments, as did the proportion of dead seeds. The proportion of dormant seeds was virtually zero, except for the high concentration sodium-based deicer, for which the proportion was about 10%. Under control conditions, most seeds germinated by the first assessment. This pattern was similar for low and medium concentrations for all solutions, as well as the high concentration $MgCl_2$ solution. For the remaining three high concentrations, germination was either delayed to the second assessment (for both deicer products), or there was no difference in the proportions of germinating seeds between assessments (for the NaCl treatment).

Penstemon strictus (Rocky Mountain penstemon): *Penstemon strictus* was particularly impacted by moderate and high ion concentrations, and the proportions of normal seedlings were drastically reduced with increasing solution concentration (Fig. 12). Proportions of abnormal seedlings increased with solution concentration for all salt treatments, as did the proportion of dead seeds (though less so for NaCl and the sodium-based deicer). There were no dormant seeds detected for this species. Under control conditions, most seeds germinated by the second and third assessments. The highest concentration of each salt solution appeared to delay germination to the third assessment.

Poa alpina (alpine bluegrass): *P. alpina* showed no difference among the proportions of normal seedlings between the control and the low concentrations of any of the four salt treatments (Figure 13). Proportions of abnormal seedlings increased with increasing concentration for all salt treatments, as did the proportion of dead seeds. The proportion of dead seeds for the high concentration sodium-based deicer was particularly high, at over 65%. There were no dormant seeds detected for this species. Under control conditions, most seeds germinated by the second and third assessments.

Poa secunda (Sandberg bluegrass): Proportions of *P. secunda* seedlings did not differ between the control and the low and medium concentrations of any of the four salt treatments (Figure 14). Proportions of abnormal seedlings increased with concentration for all salt treatments, as did the proportion of dead seeds. The highest concentrations of all four salt solutions incited dramatically higher proportions of dead seeds (less so for $MgCl_2$). There were no dormant seeds detected for this species. Under control conditions, most seeds germinated by the first assessment. Seeds exposed to the high concentrations any of the four solutions showed delayed germination.

Schizachyrium scoparium (little bluestem): *S. scoparium* showed no difference in the proportions of normal seedlings among the control and the low concentrations of any of the four salt treatments (Figure 15). This species followed the general trend seen throughout this study; proportions of normal seedlings decreased and proportions of abnormal seedlings increased with increasing salt concentration. The proportion of dead seeds also increased with concentration increases of Mg-based deicer and $MgCl_2$ only. Under control conditions, most seeds germinated by the first assessment. Germination was delayed for most concentrations of the four solutions, except the low concentrations of the Na-based treatments.

Figures 1 through 15: Effects of two salts ($MgCl_2$ and NaCl) and two deicer products (Apex® and Ice Slicer®) in germination tests on the proportions of normal and abnormal seedlings and, dormant, and dead seeds. Means and standard error bars. Standard error of the mean (SEM) is the standard deviation of the sample mean estimate of a population mean. SEM is the sample estimate of the population standard deviation (sample standard deviation) divided by the square root of the sample size.

Figure 1. *Bouteloua curtipendula*

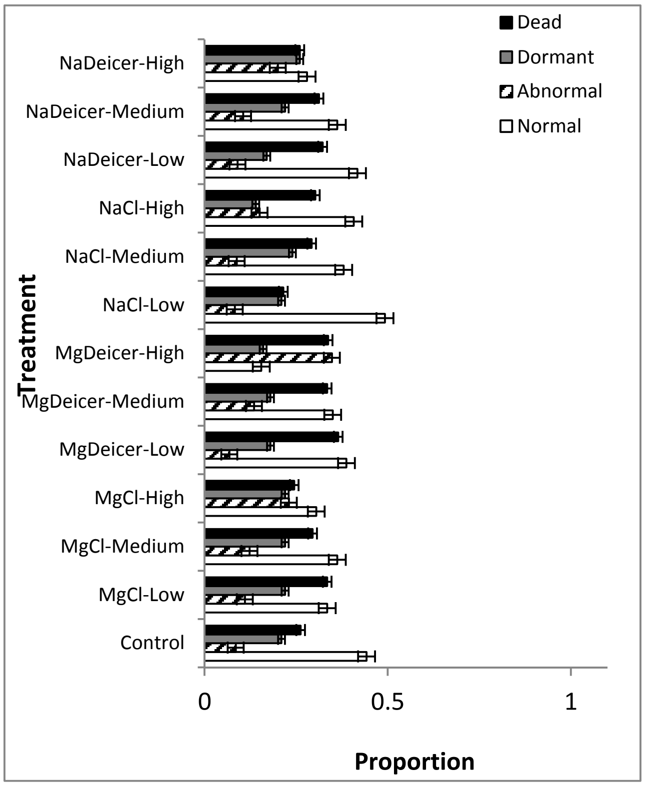


Figure 2. *Bouteloua gracilis*

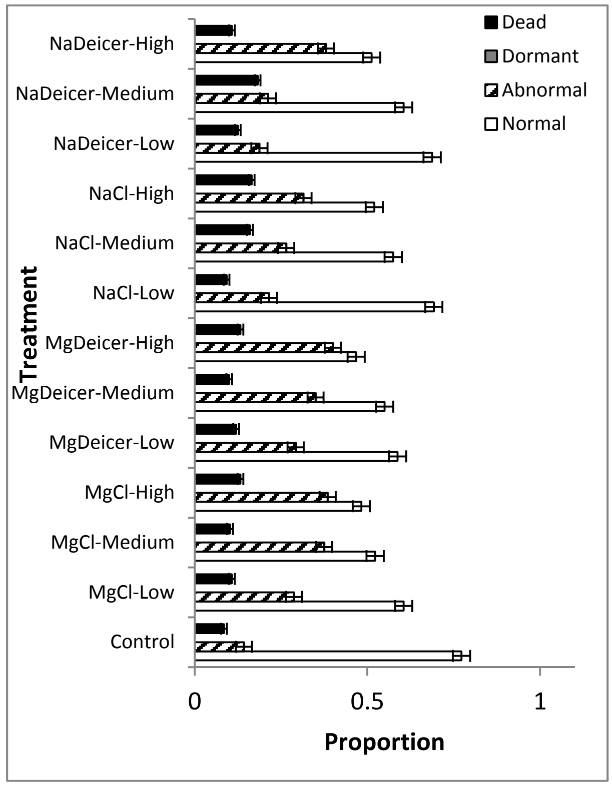


Figure 3. *Bromus marginatus*

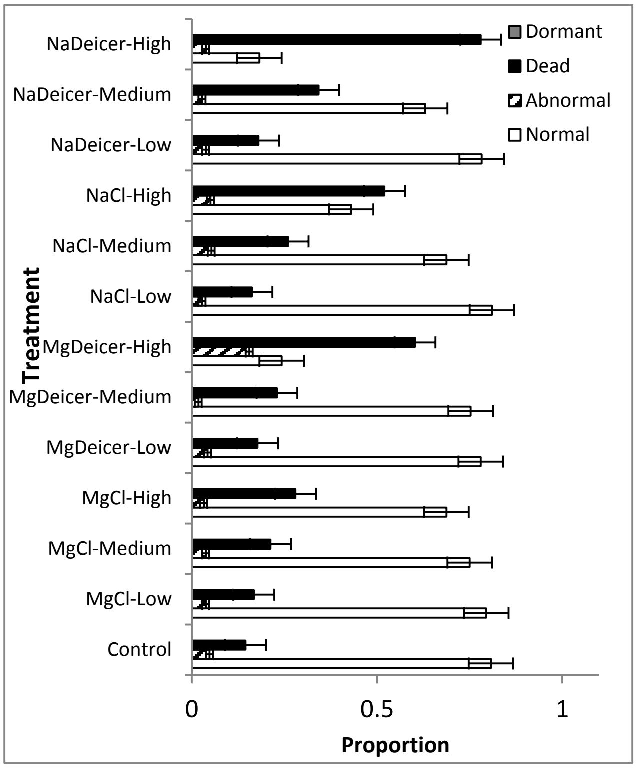


Figure 4. *Buchloe dactyoloides*

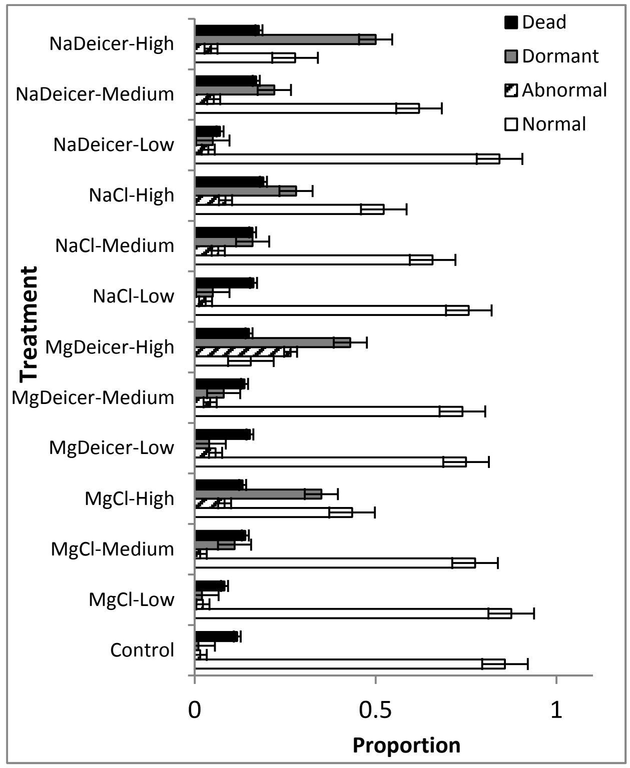


Figure 5. *Deschampsia caespitosa*

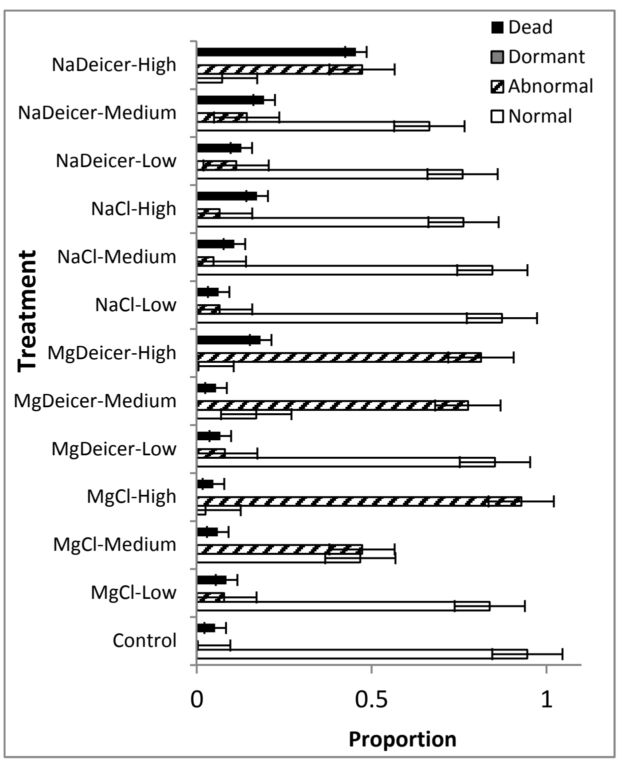


Figure 6. *Elymus trachycaulus*

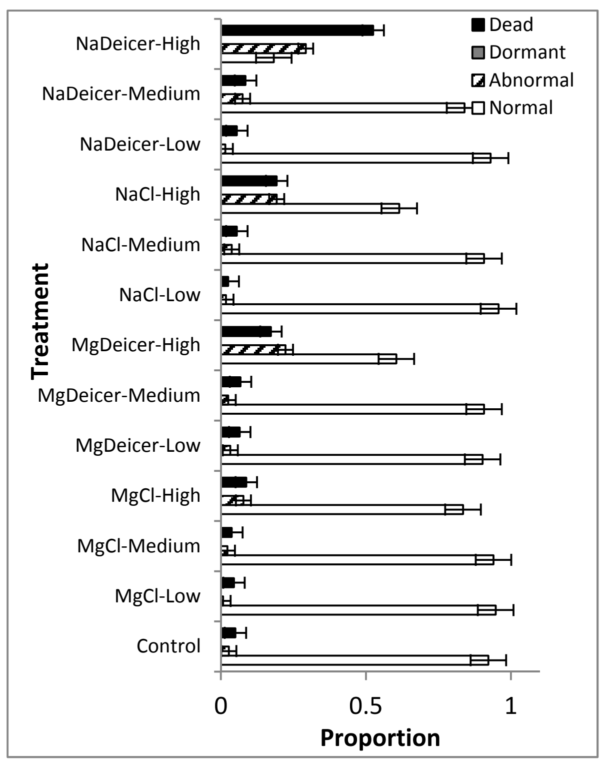


Figure 7. *Eriogonum umbellatum*

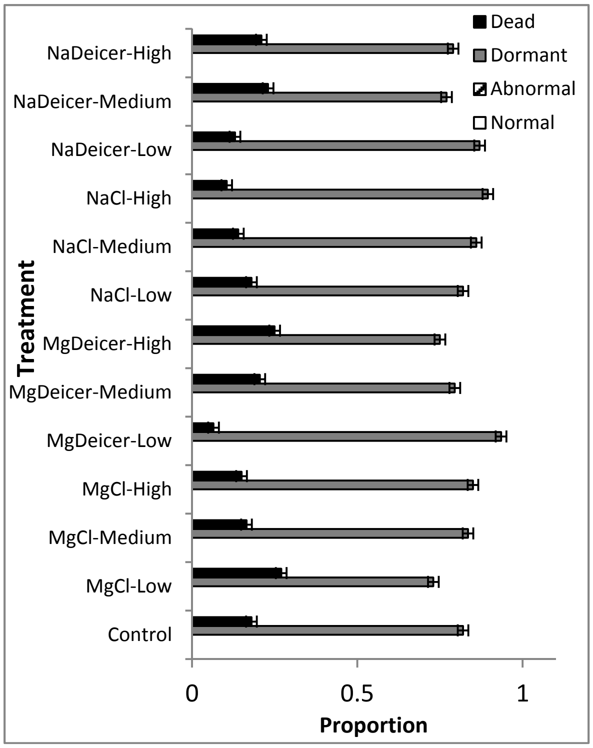


Figure 8. *Festuca ovina*

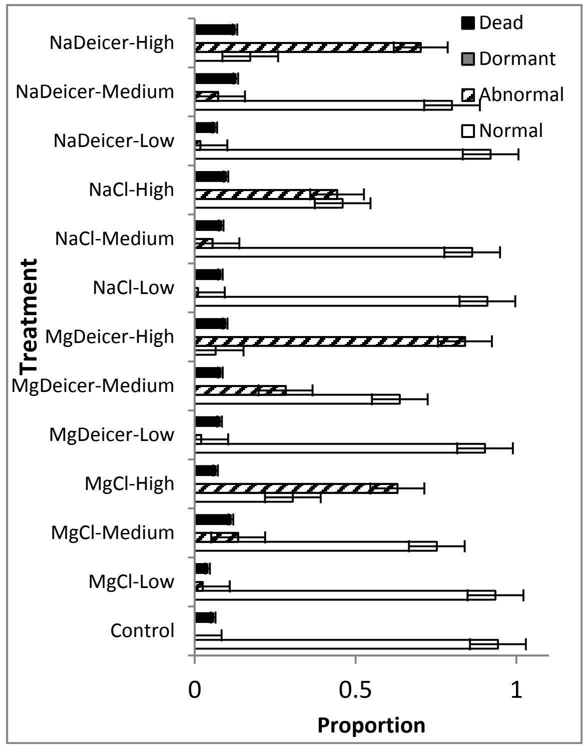


Figure 9. *Festuca saximontana*

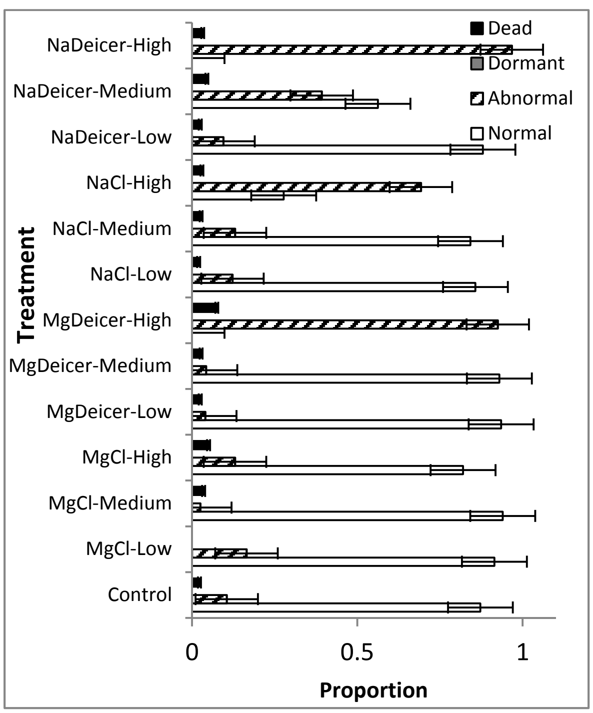


Figure 10. *Koeleria macrantha*

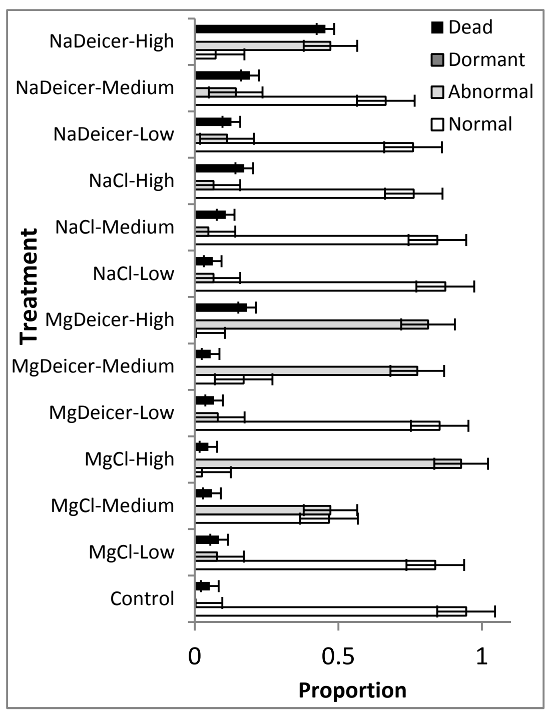


Figure 11. *Linum lewisii*

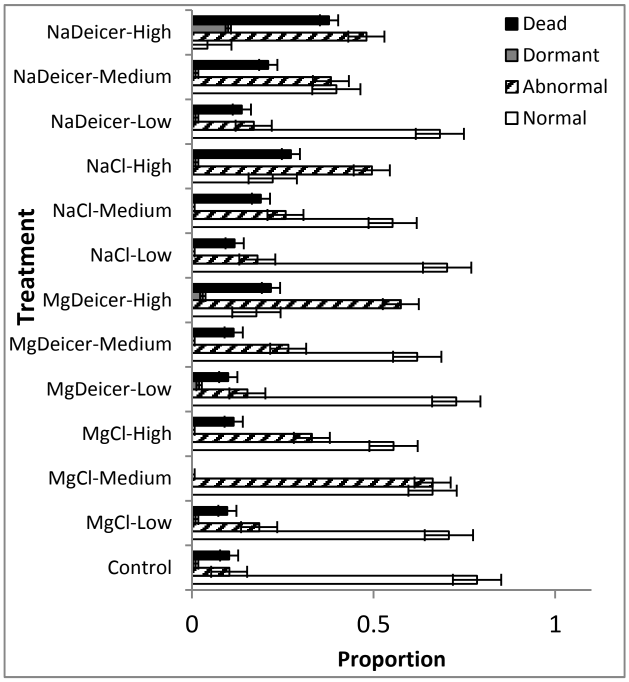


Figure 12. *Penstemon strictus*

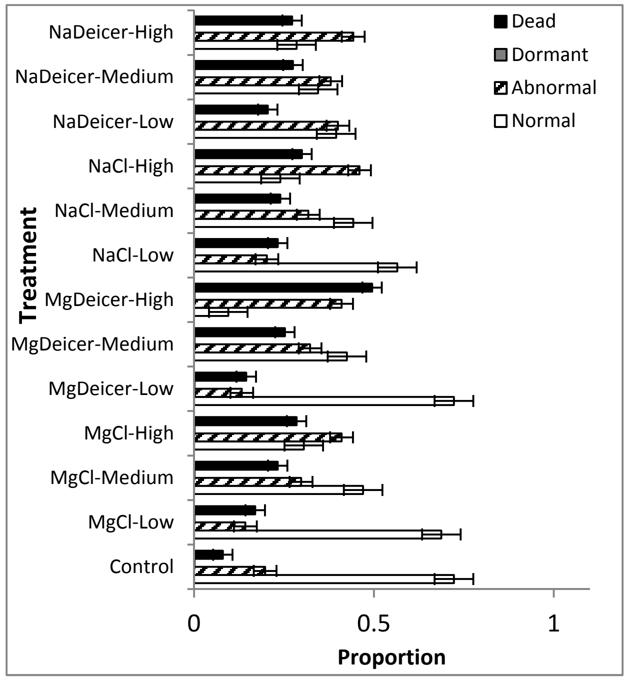


Figure 13. *Poa alpina*

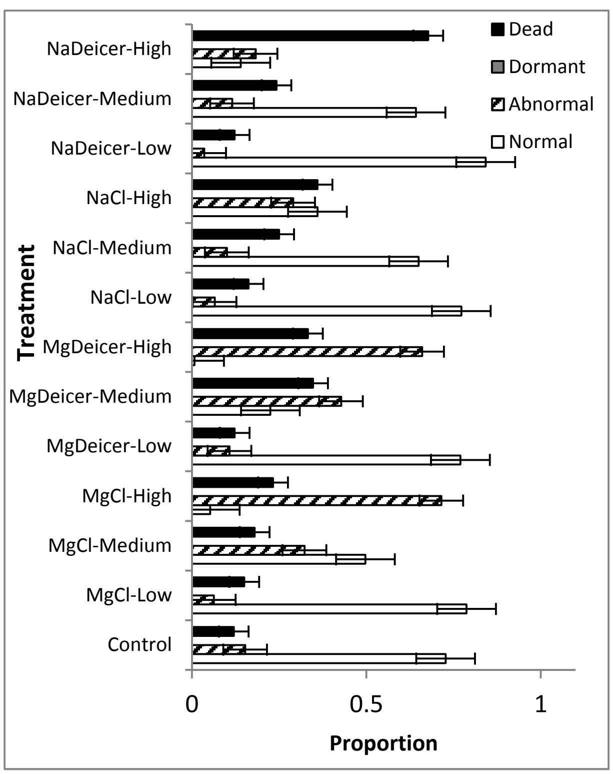


Figure 14. *Poa secunda*

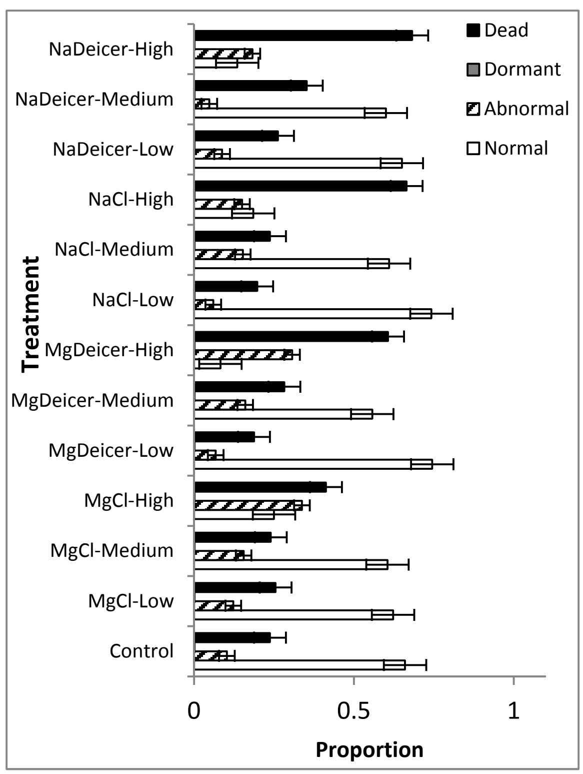
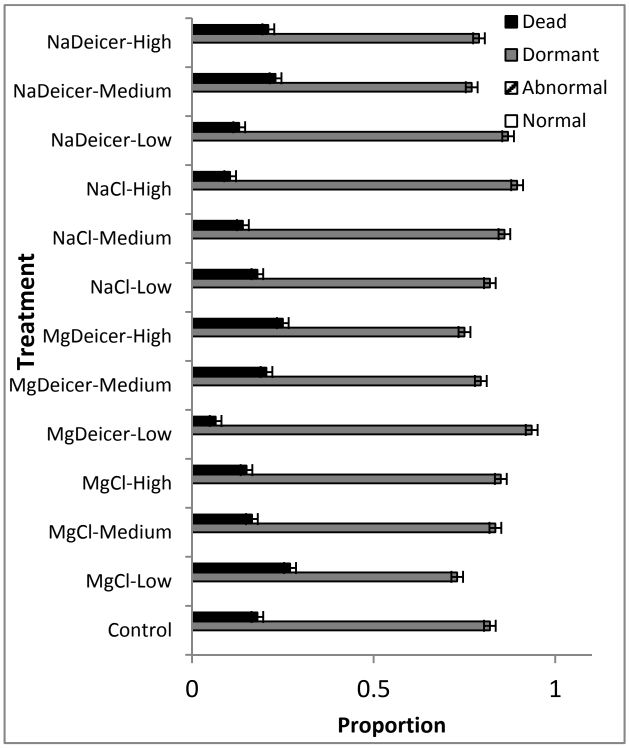


Figure 15. *Schizachyrium scoparium*



3.3 Field Study

Eight of the fifteen species tested had too few plant counts at either field site or in different soils and treatments to conduct individual data analysis on the impact of salt treatments. These species included: *Deschampsia caespitosa* (tufted hairgrass); *Poa alpina* (alpine bluegrass); *Poa sandbergii* (sandberg bluegrass); *Linum lewisii* (Lewis flax); *Penstemon strictus* (rocky mountain penstemon); *Eriogonum umbellatum* (sulfur flower buckwheat); *Bouteloua gracilis* (blue grama); *Koeleria macrantha* (prairie junegrass). Statistical analyses were performed on the remaining seven species, which included: *Schizachyrium scoparium* (little bluestem), *Elymus trachycaulus* (slender wheatgrass); *Festuca ovina* (sheep fescue); *Festuca saximontana* (rocky mountain fescue); *Bromus marginatus* (mountain brome); *Bouteloua curtipendula* (sideoats grama); *Buchloe dactyloides* (buffalograss).

Salt treatments had no impact on the average numbers of plants or biomass for any of the seven species, except the two *Festuca* species grown only at the high elevation site. For more details see Appendix B, Figure B-1. The moderate and high concentrations of $MgCl_2$ and high concentration of NaCl reduced the number and biomass of *F. saximontana* growing in topsoil, but did not affect *F. ovina* growing in topsoil. Surprisingly, plants growing in sandy soil and in some gravel combinations with the moderate and high concentrations of both $MgCl_2$ and NaCl had more biomass than the controls (Figures 16 and 17).

Soil type had a major impact on total number of plants and biomass index especially at the high elevation site since more plants grew there than at the low elevation site. See Figures 18-20 for biomass index and Appendix B, Figures B-2 to B-7. Topsoil had the most plants and highest biomass index at both locations. Gravel soil did not provide conditions for many species to germinate and grow. However, a few species such as *Elymus trachycaulus* and *Eriogonum umbellatum* were able to grow on the gravel (Figures 18 through 20). Biomass index did not differ from the pattern seen for the total living plants, so plant height was equivalent with the number of plants that could germinate and grow at both field sites.

Plant counts and biomass indices were higher at the high elevation site for most of the five species planted at both locations (Figures 18 through 20). There was no difference in biomass or plant counts between spring and fall plantings at the low elevation site, and at the high elevation site, two species (*Elymus trachycaulus* and *Erigonum umbellatum*) had more biomass when planted in the fall than in the spring (Figures18 through 20).

3.4 Species Performance at the Low Elevation Field Site

All ten species germinated and grew but the counts were low and the biomass index was poor for all species at the Fort Collins low elevation site The only species that performed well enough to be recommended was *Elymus trachycaulus* on topsoil. The impact of planting season was not noticeable in the count or biomass data, especially since the overall counts and growth was low. The performance of the species at this site was probably affected by the lower precipitation and competition with invasive weeds even though weeding of the planters occurred every two weeks.

3.5 Species Performance at the High Elevation Field Site

All ten species tested at the Black Hawk, high elevation site germinated and grew on the topsoil treatment. The poorest performers were *Egiogonum umbellatum* and *Penstemon strictus* on the topsoil treatment. *Deschampsia caespitosa, Festuca saximontana, Linum lewsii, Penstemon strictus* and *Poa alpina* did not perform well on either sandy soil or gravel. The season we planted did not affect the performance of the species at the high elevation site except for higher biomass on *Elymus trachycaulus* and *Erigonum umbellatum* on fall planted plants.

Figure 16. Biomass index of *Festuca ovina* and *Festuca saximontana*, grown under six salt treatments and three soil types at the high elevation site, Black Hawk, CO, 2008-2009. *F. ovina*, n= 659 *F. saximontana*, n=541 Means and standard error bars. Standard error of the mean (SEM) is the standard deviation of the sample mean estimate of a population mean. SEM is the sample estimate of the population standard deviation (sample standard deviation) divided by the square root of the sample size.

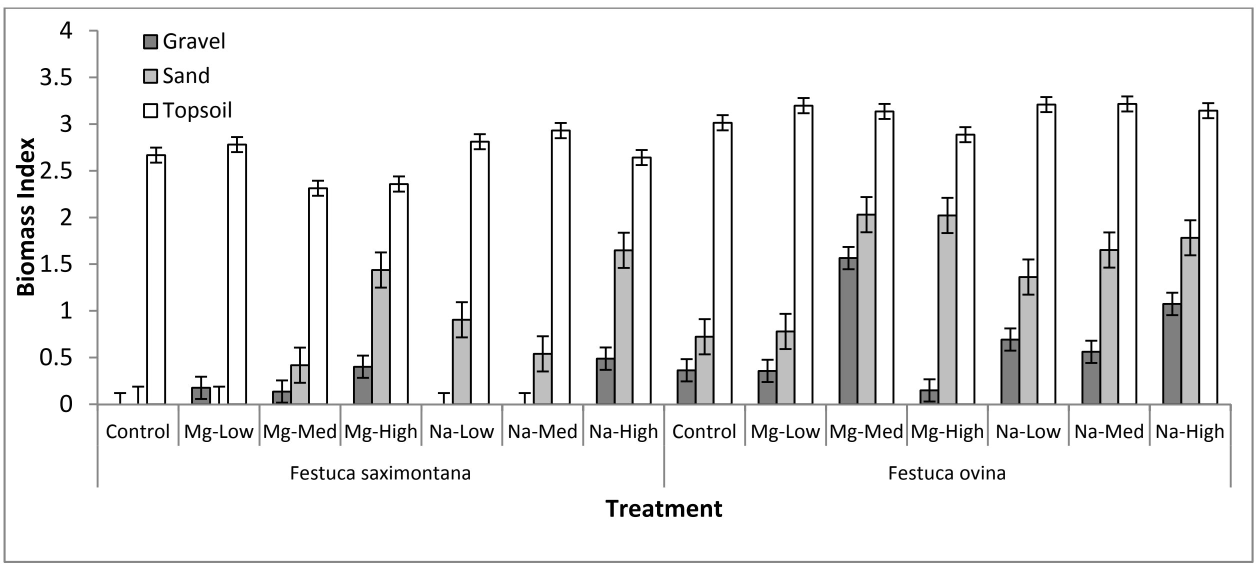


Figure 17. Biomass index, by species and soil type (averaged over all salt treatments) at the low elevation site (Fort Collins, CO), 2008-2009. Scale is $\log_{10}$-transformed count data (i.e. 1.0 = 10 plants). Means and standard error bars. Standard error of the mean (SEM) is the standard deviation of the sample mean estimate of a population mean. SEM is the sample estimate of the population standard deviation (sample standard deviation) divided by the square root of the sample size.

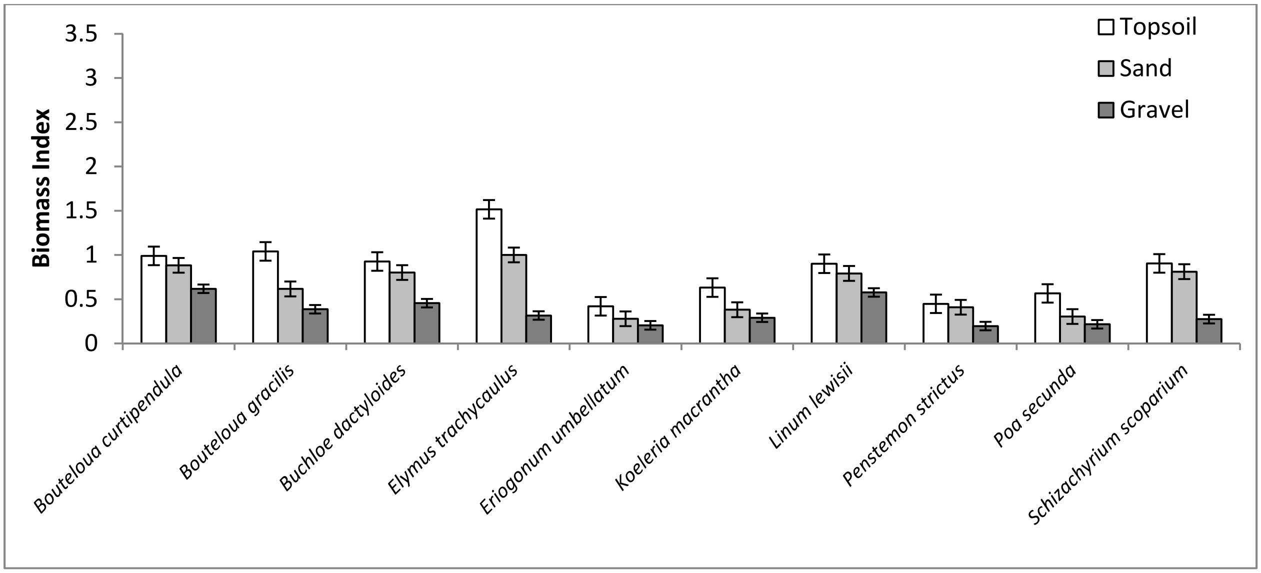


Figure 18. Biomass index, by species and soil type (averaged over all salt treatments) at the high elevation field site (Black Hawk, CO, 2008-2009). Scale is $\log_{10}$-transformed count data (i.e. 1.0 = 10 plants). Means and standard error bars. Standard error of the mean (SEM) is the standard deviation of the sample mean estimate of a population mean. SEM is the sample estimate of the population standard deviation (sample standard deviation) divided by the square root of the sample size.

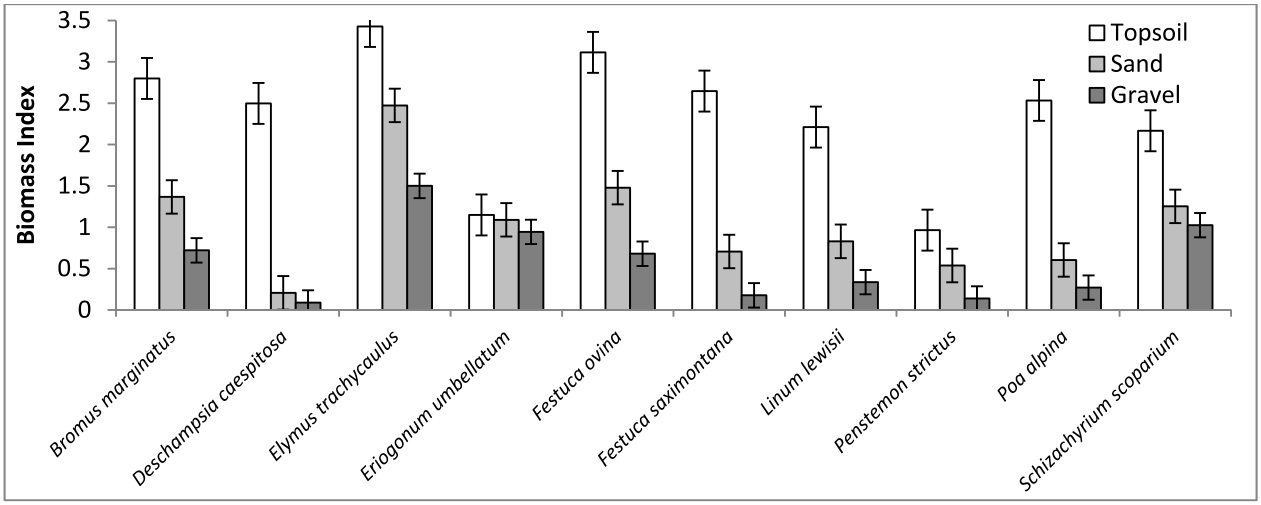


Figure 19. Biomass index, by species and planting date (averaged over all salt treatments) at the low elevation field site (Fort Collins, CO, 2008-2009). Scale is log_{10}-transformed count data (i.e. 1.0 = 10 plants). Means and standard error bars. Standard error of the mean (SEM) is the standard deviation of the sample mean estimate of a population mean. SEM is the sample estimate of the population standard deviation (sample standard deviation) divided by the square root of the sample size.

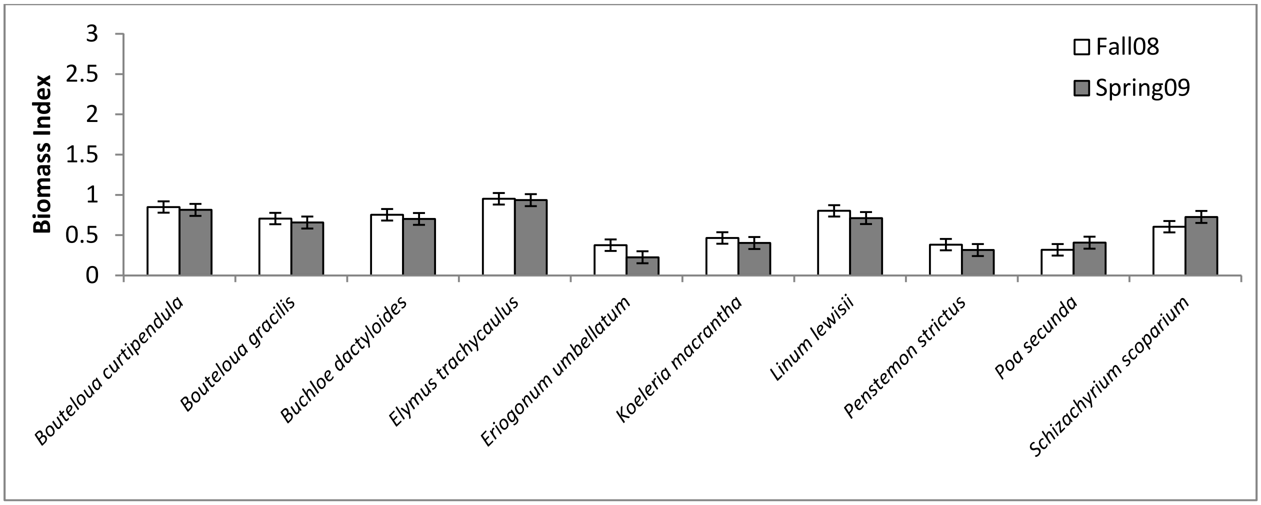
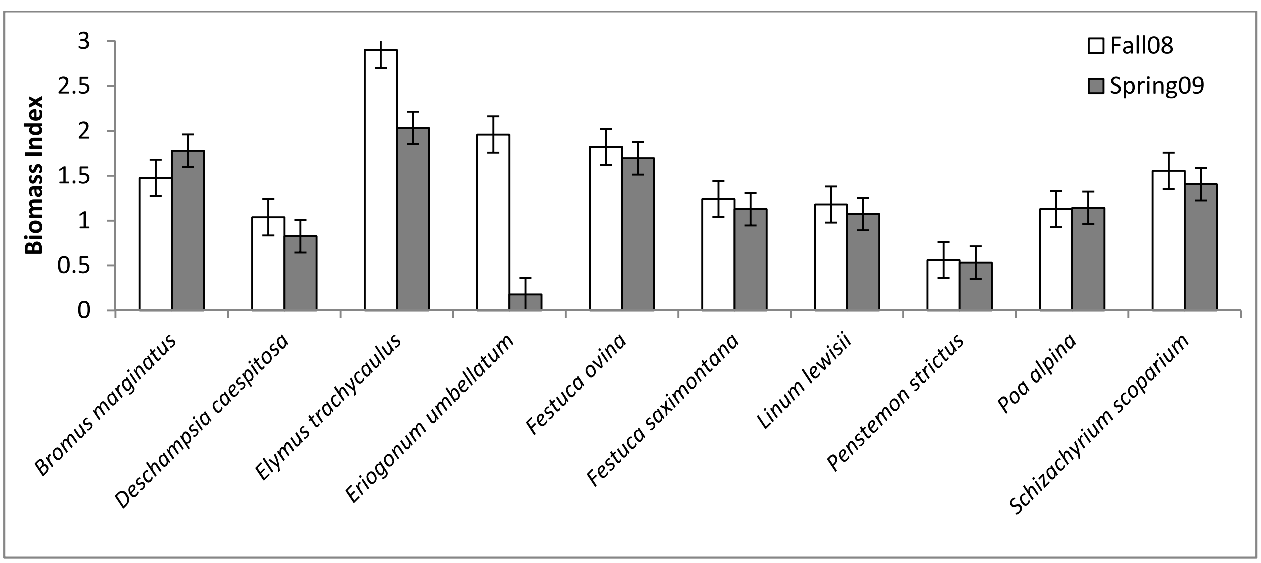


Figure 20. Biomass index, by species and planting date (averaged over all salt treatments) at the high elevation field site (Black Hawk, CO, 2008-2009). Scale is log_{10}-transformed count data (i.e. 1.0 = 10 plants). Means and standard error bars. Standard error of the mean (SEM) is the standard deviation of the sample mean estimate of a population mean. SEM is the sample estimate of the population standard deviation (sample standard deviation) divided by the square root of the sample size.



4.0 DISCUSSION

Our results indicate that the negative effect of salt on seed germination is often species-specific. Both salts (NaCl and $MgCl_2$) alone and the two deicing products containing these salts significantly impacted the germination of some of the native plant species we tested. Seven of the 15 species performed well at the low and medium concentrations of the salts and solutions so these are plants that can likely germinate in the roadside areas. The low and medium concentrations are below those found along the roadsides in May. The deicer solutions apparently contain additional materials that are inhibitory to some of the species so one should pay close attention to those results since there was more inhibition of normal seedling development. Further testing of the deicer solutions on seed germination and plant growth in controlled greenhouse and field environments would be needed to determine the actual impacts of these solutions. The bigger impact by $MgCl_2$ versus NaCl and vice versa on germination implies that plant species selection should be tempered by the preponderance of type of salt used. The five species planted only at the high elevation site had better normal germination rates than the species selected for planting only at the low elevation site. The five species planted at both sites had the overall lowest normal germination rates. Previous researchers also found a reduction in germination of Kentucky blue grass cultivars with NaCl (Horst and Taylor 1983, Torello and Symington 1984). There is limited research on the effect of $MgCl_2$ or deicing solutions, but there is a previous report that suggests $MgCl_2$ is more detrimental than NaCl to grass seedling growth (Ashraf et al 1989).

The field study reinforced the logical assumption that seed germination and subsequent growth would be more difficult on gravel and sand based soils compared with topsoil based soils. The lack of impact of salt on plant counts implies that seeds were not affected by sitting in salty soils prior to germination. The germination tests seem to contradict this evidence since salt solutions negatively impacted germination rates. Thus, it appears that the dilution and washing out of the salt in the planters by precipitation at both field locations kept the dormant seeds planted in the fall from being affected. The spring planted seeds at either location were apparently not exposed to high concentrations long enough to affect germination. We found no major or consistent effect of season of planting although some plants performed better in fall plantings. Thus seeding operations can occur at either season based on our two study locations but the chances of better moisture for germination in early spring would suggest a fall planting so the seeds were present in the spring when moisture and temperature promote germination.

The average height and number of plants were generally lower at the lower elevation field site. The most probable reason for these differences was the lower amount of precipitation and potentially greater competition from weeds, even though weeding occurred every two weeks.

The field study yielded little information about the effects of salt on plants in simulated roadside conditions. The concentration of chloride ions in the soils was low at the end of the study and apparently retreatment in the spring did not increase concentrations sufficiently (Tables 3 and 4). We speculate that precipitation between October and July reduced chloride concentrations and high amounts of residual soil water significantly diluted the treatment solutions in the spring. Total rainfall, including snow, at the low elevation site (Fort Collins Meteorological Station # 53006) was 19.3 inches and 26.3 inches at the high elevation site (Coal Creek Meteorological Station) which were 28 % and 0%, respectively, above average precipitation for the year. The soil chloride ion concentrations at the end of this study were, however, very similar to those found along I-70 during preliminary soil testing in May 2008 (Table 10). Since chloride ions are removed from the soil so readily, the experiment should be performed in a controlled situation where there is consistent flushing of soils with known salt solutions so a consistent concentration can be provided. The two species of *Festuca* were the sole species impacted by salt treatments. Surprisingly, average number of plants and average biomass were both positively affected by increased chloride ion concentrations (Figures 24 through 27). *Festuca ovina* is known to be salt-intolerant (United States Department of Agriculture, PLANTS Database) accessed November 2010, and yet it performed best under treatment with $MgCl_2$ (Figures 24 and 26). Actual ion concentrations for sand and topsoil treated with 1350 ppm $MgCl_2$ solution at the high elevation site averaged between 82 and 120 ppm chloride ions (Table 3). It is likely that salt concentrations were simply too low to negatively influence the growth of *F. ovina* and *F. saximontana*, since soil ion concentrations were less than 10% of the applied solution.

Previous studies have established that salts, and the deicing products that contain them, may accumulate along roadways and have detrimental effects on nearby vegetation (Addo et al 2004;

Goodrich et al 2009; Trahan and Peterson 2007; Zehetner et al 2009). Our results did not test that question. Our aim was to simulate the effects of winter applied salts on germination of herbaceous plant species used for revegetation along roads. Were this study to be repeated, we would recommend a number of alterations be made to the methods. First, although the field study portion was meant to replicate conditions along Colorado's highways, attaining desired ion concentrations in the soil on a continuous basis was not possible at the remote sites. The field conditions of applying an initial salt solution to the soil and then allowing leaching by precipitation does replicate the roadside condition but may not provide the correct test of salt impacts on germination and growth. Thus, a greenhouse or shadehouse setting would be a preferable alternative, and would allow for constant salt concentrations and precise application of salt solutions.

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Laboratory Germination Trials

Both salts (NaCl and $MgCl_2$) alone and the two deicing products containing these salts significantly impacted the germination of some of the native plant species we tested. Seven of the fifteen species performed well at the low and medium concentrations of the salts and solutions so these are plants that can likely germinate in the roadside areas. The deicer solutions apparently contain additional materials that are inhibitory to some of the species such as *Linum lewisii*.

Those species that were least affected by salt (regardless of type) included *Bromus marginatus*, *Buchloe dactyloides*, *Elymus trachycaulus*, *Festuca ovina*, *Festuca saximontana*, and *Poa secunda*. These top performers attained a rate of at least 60% normal germination under the low and medium concentrations of all four salt solutions. A few species were more impacted by a particular salt type or formulation than the other treatments. *Deschampsia caespitosa* and *Koeleria macrantha* were particularly sensitive to both $MgCl_2$ and the magnesium-based deicer product and less sensitive to NaCl. The presence of Na^+ was more detrimental than MgCl at the same concentration of Cl^- for several species such as *Bouteloua curtipendula*, *Bouteloua gracilis*, *Linum lewisii*, *Penstemon strictus*, and *Poa alpina*, *Penstemon strictus*). In contrast, proportions of normal *Schizachyrium scoparium* seedlings decreased with increasing concentrations of $MgCl_2$, $MgCl_2$ deicer and NaCl deicer, but not pure NaCl. The deicer products contain compounds in addition to NaCl and $MgCl_2$ and these products negatively impacted the proportion of normal seedling for species such as *Linum lewisii*, and high concentrations of both the magnesium and sodium-based deicer products had strongly negative impacts on the germination of *Festuca saximontana*.

5.2 Field Study

Eight of the fifteen species tested had too few plant counts at either field site or in different soils and treatments to conduct individual data analysis on the impact of salt treatments. We do not know if these seeds were impacted by the salt treatments or were not provided the appropriate conditions for germination and growth. Since these species did not germinate and grow in the control planters, one assumes the salt treatments were not the primary reason for lack of seedling emergence. Statistical analyses were performed on the remaining seven species, which included: *Schizachyrium scoparium* (little bluestem), *Elymus trachycaulus* (slender wheatgrass); *Festuca ovina* (sheep fescue); *Festuca saximontana* (Rocky Mountain fescue); *Bromus marginatus* (mountain brome); *Bouteloua curtipendula* (sideoats grama); and *Buchloe dactyloides* (buffalograss).

Salt concentrations were apparently diluted by rainfall and thus treatments were not what was anticipated, and thus had no impact on the average numbers of plants or biomass for any of the seven species, except the two *Festuca* species grown only at the high elevation site. The seeds were apparently not negatively impacted by sitting in the treated soils from the fall or spring planting dates. The moderate and high concentrations of $MgCl_2$ and high concentration of NaCl reduced the number and biomass of *F. saximontana* growing in topsoil but did not affect *F. ovina* growing in topsoil. Topsoil had the most plants and highest biomass index at both locations. Gravel soil did not provide conditions for many species to germinate and grow. However, a few species such as *Elymus trachycaulus* and *Eriogonum umbellatum* were able to grow on the gravel.

5.3 Recommendations

- Using the species that had the best percent germination for planting in roadside areas such as *Buchloe dactyloides, Bromus marginatus, Elymus trachycaulus, Festuca ovina, Festuca saximontana*, and *Poa secunda,* provides the best opportunity for establishing plants along highways treated with deicing products.
- If possible, planting should occur in the fall.
- Soil type had a major impact on total number of plants and biomass index, especially at the high elevation site since more plants grew there than at the low elevation site. Topsoil had the most plants and highest biomass index at both locations. Gravel soil did not provide conditions for many species to germinate and grow. However, a few species such as *Elymus trachycaulus* and *Eriogonum umbellatum* were able to grow on the gravel. Providing a better soil to establish plants in along the highway would promote more plants and better growth of the plants.

- Future studies should focus on quantifying vegetation health along the state highways so that spatial relationships of plant health and highway maintenance, site factors (soils, slopes etc), vegetation types, precipitation and other metrological factors can be assessed. With this field information and our laboratory information, best management practices can be developed for plantings alongside Colorado highways.
- Since chloride ions are readily removed from the soil, field or greenhouse experiments should be performed in a controlled situation where consistent flushing of soils with known salt solutions is feasible so a consistent concentration can be provided. After these relationships are established true field testing can be carried out.

6.0 REFERENCES

Addo, J.Q., Chenard, M., and Sanders, T.G. 2004. Road Dust Suppression: Effect on Maintenance, Stability, Safety and the Environment (Phases 1-3). Mountain Plains Consortium, Report Number: MPC-04-156, 64 pp.

Alshammary, S.F., Qian, Y.L. and Wallner, S.J. 2003. Growth response of four turfgrass species to salinity. Agricultural Water Management 66:97-111.

Ashraf, M., McNeilly, T., and Bradshaw, A. D. 1989. The potential for evolution of tolerance to sodium chloride, calcium chloride, magnesium chloride and seawater in four grass species. New Phytologist 112: 245-254.

Beaton, L.L., Dudley, S.A. 2007. The impact of solute leaching on the salt tolerance during germination of the common roadside plant *Dipsacus fullonum* subsp. *sylvestris* (Disaceae). Int. J. Plant Sci. 168:317-324.

Beaton, L.L., Dudley, S.A. 2007. The impact of solute leaching on the salt tolerance during germination of the common roadside plant *Dipsacus fullonum* subsp. *sylvestris* (Disaceae). Int. J. Plant Sci. 168:317-324.

DiTommaso, A. 2004. Germination behavior of common ragweed (Ambrosia artemisifolia) populations across a range of salinities. Weed Sci. 52:1002-1009.

Bowman, D.C., Devitt, D.A., and W. W. Miller. 2000. The Effect of Salinity on Nitrate Leaching from Tall Fescue Turfgrass. ACS Symposium Series. 743: 164-178.

Camberato, J. J. and Peterson, P.D., and Martin, S. B. 2006. Salinity and salinity tolerance alter rapid blight in Kentucky bluegrass, perennial ryegrass, and slender creeping red fescue. Applied Turfgrass Science doi:1094/ATS-2006-0213-01-RS.

Carrow, R.N., and R.R. Duncan. 1998. Salt affected turfgrass sites: Assessment and management. Ann Arbor Press, Chelsea, MI.

Cunningham, M.A., Snyder, E., Yonkin, D., Ross, M., and Toren Elsen. 2008. Accumulation of deicing salts in soils in an urban environment. Urban Ecosystem 11:17-31.

Dobson, M.C. (1991). De-icing salt damage to trees and shrubs. Forestry Commission Bulletin, 101, 1-64.

Environment Canada and Health Canada. 2001. Canadian Environmental Protection Act, 1999. Priority Substances List Assessment Report: Road Salts. 180 pp.

Ervin, E.H. and Koski, A.J. 1997. Comparison of modified atmometer estimates of turfgrass evapotranspiration with Kimberly-Penman alfalfa reference evapotranspiration. Int. Turf. Soc. Res. J. 8:663-670.

Ervin, E. H and Koski, A. J. 1998. Drought avoidance aspects and crop coefficients of Kentucky bluegrass and tall fescue turfs in the semiarid West. Crop Sci. 38:788-7 95.

Marion Fischel (The SeaCrest Group). 2001. Evaluation Of Selected Deicers Based On A Review Of The Literature. Report No. CDOT-DTD-R-2001-15.

Fu, J., Koski, A. and Qian, Y. 2005. Responses of creeping bentgrass to salinity and mowing management: growth and turf quality. Hortscience 40:464-467.

Goodrich, B.A., Koski, R.D., and W.R. Jacobi. 2009. Condition of soils and vegetation along roads treated with magnesium chloride for dust suppression. Water Air and Soil Pollution 198:165-188.

Greub, L.J., Drolsom, P. N. Rohweder, D. A. 1985. Salt tolerances of grasses and legumes of roadside use. Agronomy Journal 77: 76-80.

Hall, R., Hofstra, G. and G.P. Lumis. (1972). Effects of deicing salt on eastern white pine: foliar injury, growth suppression and seasonal changes in foliar concentrations of sodium and chloride. Canadian Journal of Forest Research, 2, 244–249.

Hofstra, G. and R. Hall. (1971). Injury on roadside trees: leaf injury on pine and white cedar in relation to foliar levels of sodium and chloride. Canadian Journal of Botany, 49, 613-622.

Hofstra, G., Hall, R., and Lumis, G. P. (1979). Studies of salt induced damage to roadside plants in Ontario. Journal of Arboriculture, 5, 25–31.

Host, G.L. and Taylor, R. M. 1983. Germination and initial growth of Kentucky bluegrass in soluble salts. Agronomy Journal 75:679-681.

Keeley, S.J. and A.J. Koski. 2001. Dehydration avoidance of diverse *Poa pratensis* cultivars and cultivar groups in a semi-arid climate. International Turfgrass Society Research Journal. 9:311-316.

Keeley, S. J., and A. J. Koski. 2002. Root distribution and ET as related to drought avoidance in *Poa pratensis*. In Thain, Eric (ed.) Science and Golf IV. London: Routledge.

Koski, A.J., J.R. Street and T.K. Danneberger. 1988. Prediction of Kentucky bluegrass root growth using degree-day accumulation. Crop Sci. 28:848-850.

Koski, A.J. 1993. Grass identification. J. Natural Resources Life Sciences Education 22(2):53-54.

Kramer, P.J. and J.S. Boyer. (1995). Water Relations of Plants and Soils. (New York: Academic Press).

Munck, I.A., Bennett, C. M., Camilli, K. S. and Nowak, R.S. 2010. Long-term impact of de-icing salts on tree health in the Lake Tahoe Basin: Environmental influences and interactions with insects and diseases. Forest Ecology and Management in press.

Norrstrom, A.C. and E. Bergstedt. (2001). The impact of road de-icing salts (NaCl) on colloid dispersion and base cation pools in roadside soils. Water, Air, and Soil Pollution, 127, 281-299.

Piatt, J.R. and P.D. Krause. (1974). Road and site characteristics that influence road salt distribution and damage to roadside aspen trees. Water, Air and Soil Pollution, 3, 301-304.

Qian, Y.L., Ball, S., Tan, Z., Koski, A.J, and S.J. Wilhelm. 2001. Low temperature tolerance of six cultivars of buffalograss. Crop Sci. 41:1174-1178.

Qian, Y.L., Koski, A.J., and R. Welton. 2001. Amending isolite and zeolite in sand under saline conditions: leachate composition and salt deposition. HortScience. 36:717-720.

Qian, Y.L., Follett, R.F., Wilhelm, S., Koski, A.J. and Shahba, M.A. 2004. Carbon isotope discrimination of three Kentucky bluegrass cultivars with contrasting salinity tolerance. Agron. J. 96:571-575.

Qian, Y.L. and Fu, J.M. 2005. Response of creeping bentgrass to salinity and mowing management: Carbohydrate availability and ion accumulation. HortScience 40:2170-2174.

Richburg, Julie A., Patterson, William A. III., and Frank Lowenstein. 2001. Effects of Road Salts and *Phragmites australis* Invasion of a Western Massachusetts Calcareous Lake Basin Fen. Wetlands. 21(2): 247- 255.

Robins, Joseph G., Bushman, Shawn, and Blair L. Waldron. 2009. Variation within *Poa* Germplasm for Salinity Tolerance. HortScience. 44(6): 1517-1521.

Shahba, M. A., Qian, Y.L., Hughes, H.G., Koski, A.J. and Christensen, D. 2003. Relationship of carbohydrates and cold hardiness in six saltgrass accessions. Crop Sci. 43:2148-2153.

Suplick-Ploense, M.R., Qian, Y.L., and J.C. Read. 2002. Relative NaCl tolerance of Kentucky bluegrass, Texas bluegrass, and their hybrids. Crop Sci. 42:2025-2030.

Torello, W. A. and Symington, A. G. 1984. Screening of turfgrass species and cultivars for NaCl tolerance. Plant and Soil 82:155-161.

Trahan, N. A., & Peterson, C. M. (2005). Factors Impacting the Health of Roadside Vegetation. Colorado Department of Transportation Research Branch Final Report No., CDOTDTD-R-2005-12.

USDA, NRCS. 2010. The PLANTS Database (http://plants.usda.gov). National Plant Data Center, Baton Rouge, LA 70874-4490 USA.

Viskari, E. and L. Karenlampi. (2000). Roadside Scots pine as an indicator of deicing salt use. Water, Air and Soil Pollution, 122, 409-423.

Westing, A.H. 1969. Plants and soils in the roadside environment. Phytopathology 59:1174-1181.

White, P.J. and M.R. Broadley. (2001). Chloride in soils and its uptake and movement within the plant: a review. Annals of Botany, 88, 967-988.

Zehetner, Franz, Rosenfellner, Ulricke, Mentler, Axel, and Martin H. Gerzabek. 2009. Distribution of Road Salt Residues, Heavy Metals, and Polycyclic Aromatic Hydrocarbons across a Highway-Forest Interface. Water Air Soil Pollut. 198:125-132.

APPENDIX A. SUPPLEMENTAL TABLES

Table A-1. Analysis of salt solutions used at the high elevation field site, Black Hawk, CO.

Salt Treatment	Concentration ppm	Cl^-, ppm		Na_2, ppm		Mg_2, ppm	
		Fall '08 ppm	Spring '09	Fall '08	Spring '09	Fall '08	Spring '09
NaCl	300	196	491	42	114	22	47
NaCl	1350	197	1832	68	785	22	49
NaCl	3000	1740	3648	934	1023	22	46
$MgCl_2$	300	157	611	21	28	29	138
$MgCl_2$	1350	1720	1992	28	35	393	483
$MgCl_2$	3000	3185	3490	166	50	811	877
Control	--	150	408	18	27	23	52

Table A-2. Analysis of salt solutions used at the low elevation field site, Fort Collins, CO.

Salt Treatment	Concentration	Cl^-, ppm		Na_2, ppm		Mg_2, ppm	
		Fall '08	Spring '09	Fall '08	Spring '09	Fall '08	Spring '09
NaCl	300	292	327	200	217	1	5
NaCl	1350	1407	959	866	21	2	9
NaCl	3000	3006	1340	2039	2176	0.3	2
$MgCl_2$	300	303	334	12	12	115	115
$MgCl_2$	1350	1435	1010	40	857	510	403
$MgCl_2$	3000	2824	1370	34	32	1202	918
Control	--	4	--	8	--	2	--

Table A-3. Association of Seed Analysts (AOSA) standards for seed germination trials for each of the 15 plant species.

Species	Substrata[z]	Temperature[y] (°C)	First count (days)[x]	Final count (days)[v]	Specific requirements and notes[u]	Fresh and dormant seed[t]
Bouteloua dactyloides (Buffalo grass)	P	20-35	7	14	Light; KNO3	Prechill at 5°C for 2 weeks. Ungerminated seeds: see sec. 6.2e and 6.9m
Bromus marginatus (Mountain brome)	P	20-30	6	14	Light	
Elymus trachycaulus subsp. trachycaulus (Slender wheatgrass)	P, TB	20-30	5	14	Light; KNO3	Prechill at 5° or 10°C for 5 days. If still dormant on 10th day of germination period, rechill 2 days then place at 20-30°C for 4 days
Bouteloua gracilis (Blue grama)	P, TB	20-30	7	14	Light	KNO3. Ungerminated seeds: see sec. 6.2e and 6.9m
Schizachyrium scoparium (Little Bluestem)	P, TS	20-30	7	14	Light	Ungerminated seeds: see sec. 6.2e and 6.9m
Poa secunda (Sandberg bluegrass)	P	20-30	7	21	Light; KNO3	
Koeleria macrantha (Prairie junegrass)	TB	20-30	7	21		
Deschampsia cespitosa (Tufted hairgrass)	P	20-30	7	16		Prechill 7 days
Bouteloua curtipendula (Sideoats grama)	P	15-30	7	14	Light; KNO3	Ungerminated seeds: see sec. 6.2e and 6.9m
Festuca saximontana (Rocky mountain fescue)	TB	15-25	5	21		
Poa alpina (Alpine bluegrass)	P	15-25	7	14	Filter Paper; 5 day prechill	
Festuca ovina (Sheep fescue)	P	15-25	7	21		
Penstemon strictus (Rocky mountain penstemon)	P	15	7	21	Light	
Eriogonum umbellatum (Sulfur flower buckwheat)	TB	15	5	28		
Linum lewisii (Lewis flax)	TB	15; 10-20	10	28	Light. Paired tests. Prechill 28 days at 2-5°C	Ungerminated seeds: see sec. 4.2e and 4.9k

[z] 'Substrata' refers to placement of the seeds in the germination box: TB = 'top of blotter'; P = 'top of blotter-petri'.

[y] Temperature: diurnal temperature range for given species

[x] First count: the day of first germination assessment, from the start of the germination trial

[v] Final count: the day of last germination assessment, from the start of the germination trial

[u] Additional specifications for germination

[t] Additional regulations for germination; 'sec' refers to sections in the *Rules for Testing Seeds* Handbook (AOSA).

Table A-4. Monthly precipitation (inches) for the 2008-09 water year at Fort Collins and Black Hawk, CO field sites.

	Monthly Precipitation (in)													
	2008			2009										
Station[1]	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	May - Sept Total (in)	Water Year (Oct - Sept) Total (in)
53005 FORT COLLINS	0.81	0.01	0.53	0.28	0.16	0.93	4.44	2.23	5.03	3.95	0.22	0.67	12.10	19.26
51681 COAL CREEK	1.30	0.43	1.45	0.91	0.38	1.61	8.40	2.69	3.61	2.72	0.56	2.21	11.79	26.27

[1] Station data from Colorado Climate Center 2008-09 Water Year Data for Colorado (http://climate.colostate.edu/coloradowater.php)

APPENDIX B. SUPPLEMENTAL FIGURES

Figure B-1. Number of living plants of *Festuca ovina* and *Festuca saximontana*, grown under six salt treatments and three soil types, at the high elevation field site (Black Hawk, CO) 2008-2009. *F. ovina*, n= 659 *F. saximontana*, n=541 Means and standard error bars. Standard error of the mean (SEM) is the standard deviation of the sample mean estimate of a population mean. SEM is the sample estimate of the population standard deviation (sample standard deviation) divided by the square root of the sample size.

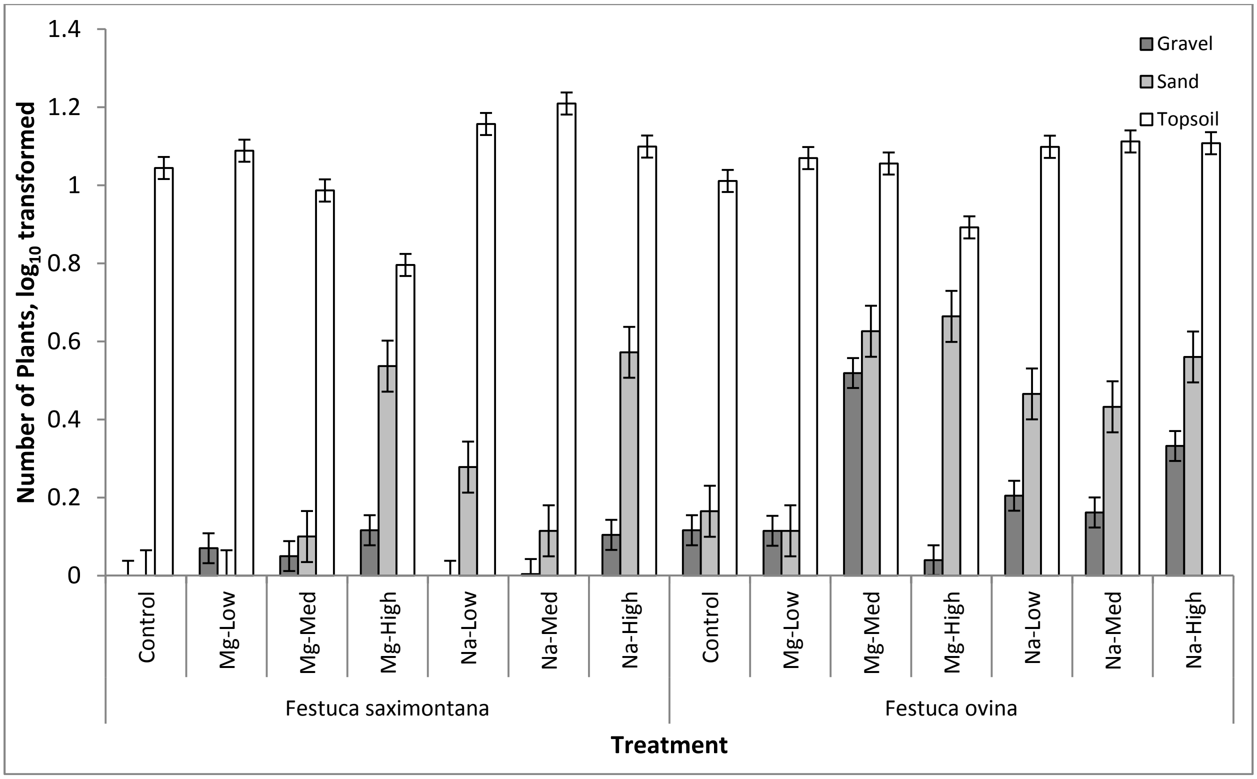


Figure B-2. Biomass index of *Festua ovina* and *Festuca saximontana*, grown under six salt treatments at the high elevation field site (Black Hawk, CO) 2008-2009. n=252, *F. ovina*, n= 248 *F. saximontana*. Means and standard error bars. Standard error of the mean (SEM) is the standard deviation of the sample mean estimate of a population mean. SEM is the sample estimate of the population standard deviation (sample standard deviation) divided by the square root of the sample size.

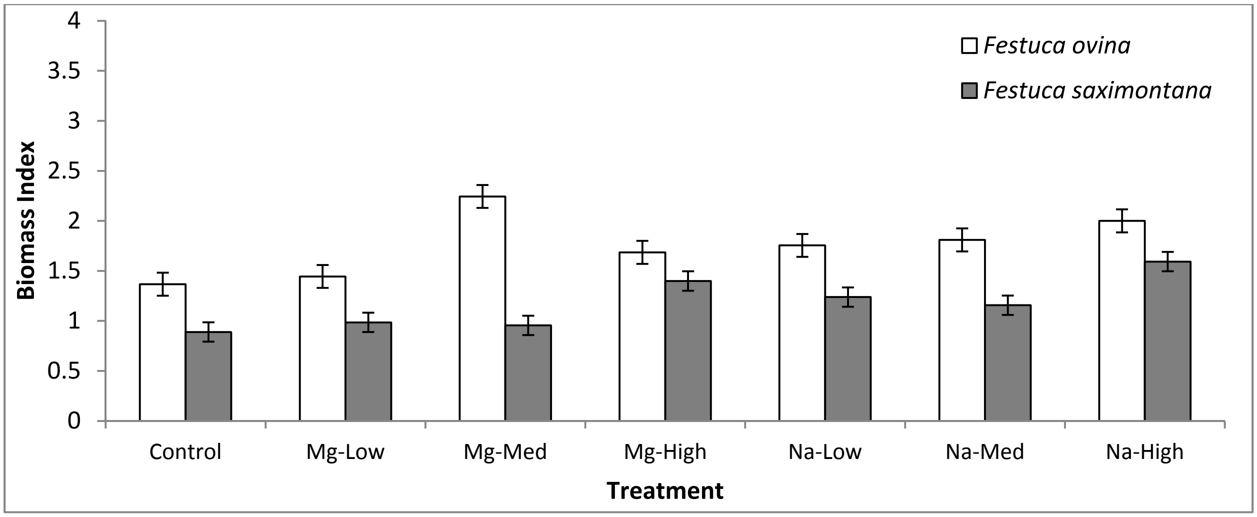


Figure B-3. Number of living plants of *Festuca ovina* and *Festuca saximontana*, grown under six salt treatments, high elevation field site (Black Hawk, CO) 2008-2009. n=252, *F. ovina*, n= 248 *F. saximontana* Means and standard error bars. Standard error of the mean (SEM) is the standard deviation of the sample mean estimate of a population mean. SEM is the sample estimate of the population standard deviation (sample standard deviation) divided by the square root of the sample size.

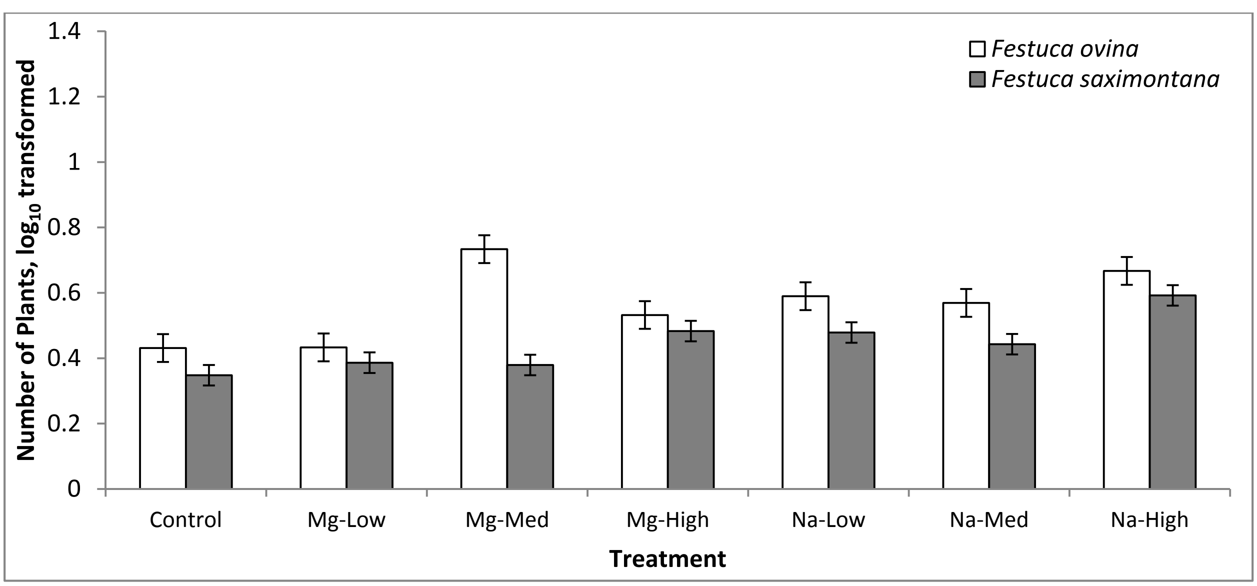
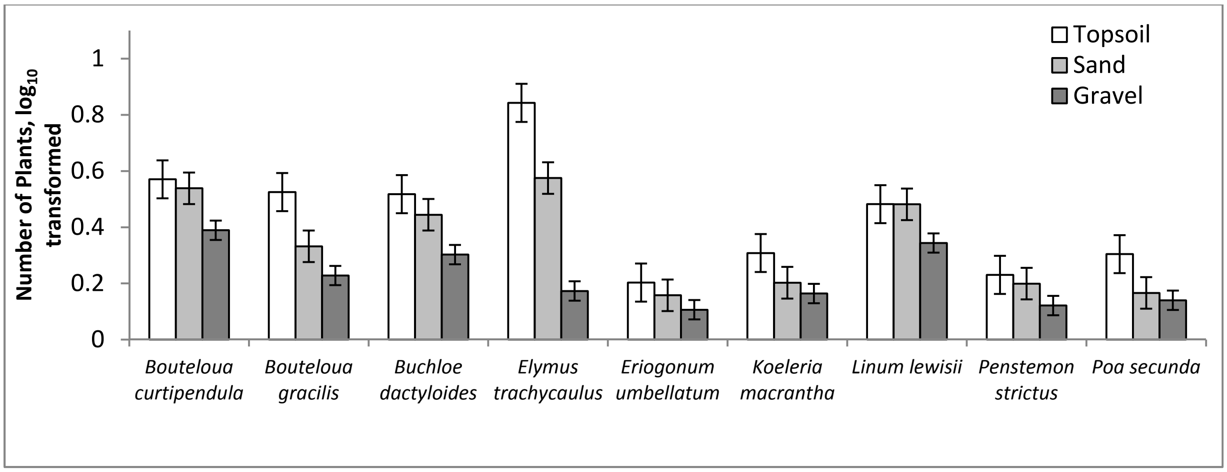


Figure B-4. Number of living plants, by species[z] and soil type (averaged over all salt treatments) at the low elevation field site (Fort Collins, CO) 2008-2009. Scale is $\log_{10}$-transformed count data (i.e. 1.0 = 10 plants). Means and standard error bars. Standard error of the mean (SEM) is the standard deviation of the sample mean estimate of a population mean. SEM is the sample estimate of the population standard deviation (sample standard deviation) divided by the square root of the sample size.



[z] *Schizachyrium scoparium* was not included in this analysis, due to low numbers of plants.

Figure B-5. Number of living plants, by species and soil type (averaged over all salt treatments) at the high elevation field site (Black Hawk, CO), 2008-2009. Scale is log_{10}-transformed count data (i.e. 1.0 = 10 plants). Means and standard error bars. Standard error of the mean (SEM) is the standard deviation of the sample mean estimate of a population mean. SEM is the sample estimate of the population standard deviation (sample standard deviation) divided by the square root of the sample size.

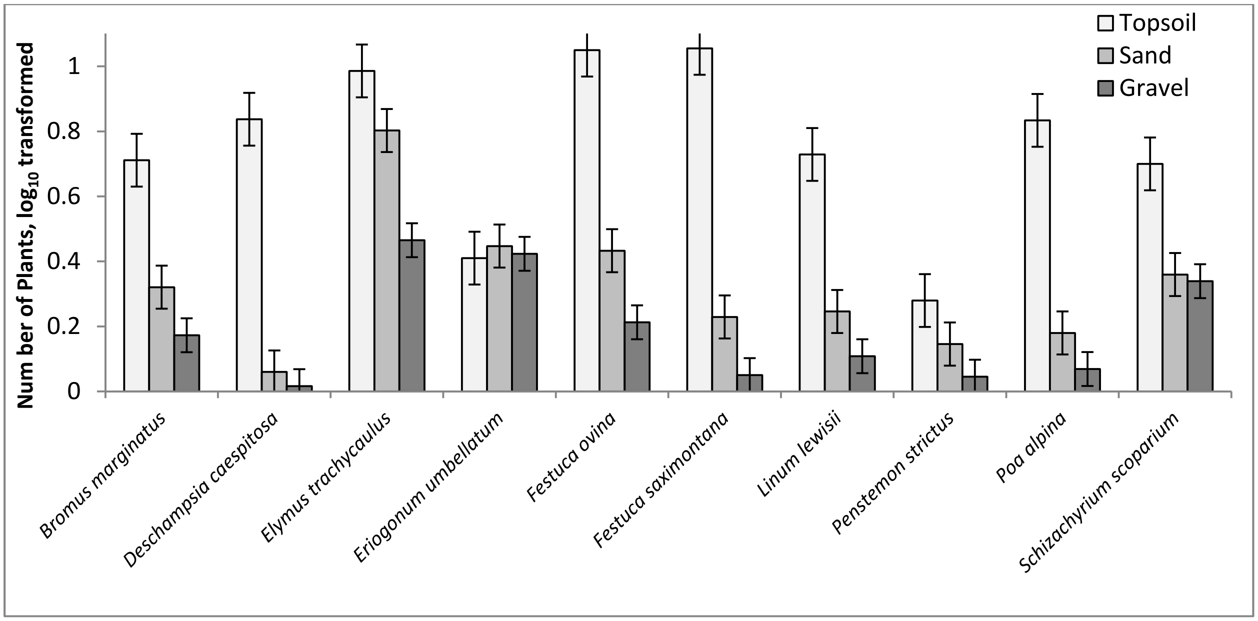


Figure B-6. Number of living plants, by species and planting date (averaged over all salt treatments) at the low elevation field site (Fort Collins, CO) 2008-2009. Scale is $\log_{10}$-transformed count data (i.e. 1.0 = 10 plants). Means and standard error bars. Standard error of the mean (SEM) is the standard deviation of the sample mean estimate of a population mean. SEM is the sample estimate of the population standard deviation (sample standard deviation) divided by the square root of the sample size.

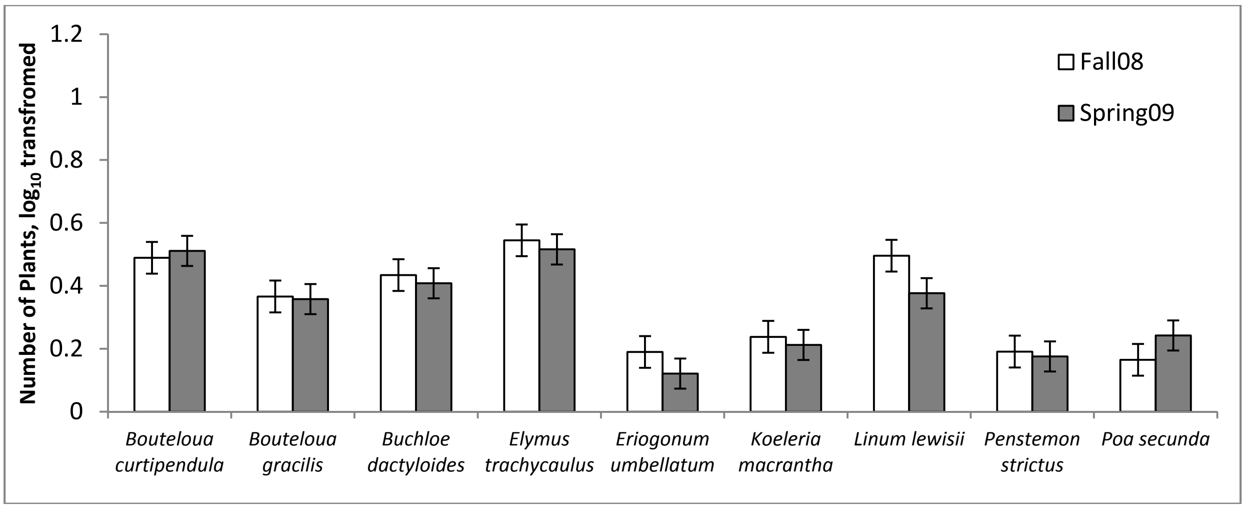


Figure B-7. Number of living plants, by species and planting date (averaged over all salt treatments) at the high elevation site (Black Hawk, CO) 2008-2009. Scale is $\log_{10}$-transformed count data (i.e. 1.0 = 10 plants). Means and standard error bars. Standard error of the mean (SEM) is the standard deviation of the sample mean estimate of a population mean. SEM is the sample estimate of the population standard deviation (sample standard deviation) divided by the square root of the sample size.