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Assessment of Highway Deicing Impacts to Roadside Pines in the Black Hills

Study SD2006-01-F
Final Report

Plant Science Department
South Dakota State University
Brookings, SD, 57007

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Jim Blodgett........................USDA Forest Service
Clarence Bowman...............SDDOT Custer Area
David Huft ....SDDOT Research
Dan Johnston........................... SDDOT Research
Ray McLaughlin................. SDDOT Custer Area
Robert Smith................ SDDOT Rapid City Area
Danny Stetler............... SDDOT Rapid City Area

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16. Abstract

During the early to mid-2000s the public expressed concern regarding the poor appearance of the ponderosa pines (*Pinus ponderosa*) along highways in the Black Hills. Deicing road salts were thought to be the cause for the change in appearance. The objectives of this study were to define the extent of discoloration and dieback of pines along the state highways in the Black Hills, to determine if the decline and discoloration of the pines were due to deicing salts and investigate other stressors that may have been responsible for the symptoms. A total of 346 miles of state highways were surveyed and observations were made at one-mile intervals along the roads. Pines occurred at approximately two-thirds of the points and the majority of these trees exhibited little dieback during the 2007 survey, but this increased to the majority for the 2011 survey. A reverse trend was noted with foliage color, where the majority of pines on the points were discolored in 2007 but exhibited normal color by 2011. Dieback is due to the accumulation of past stresses while discoloration is an indicator of current stress. Soil and pine foliage samples were collected from four sites with roadside pines expressing canopy discoloration and dieback and another four sites where the pines were asymptomatic. Soil samples were collected from the sites at three feet and 20 feet from the pavement edge and 60 feet from the road centerline and analyzed for chloride, magnesium, and sodium. Foliage samples were collected from the nearest pine at the 20 and 60-foot soil sampling locations. There were no pines at three feet from the road edge. There were significant differences in foliage concentrations of sodium and chloride between sites containing symptomatic or asymptomatic trees at 20 feet from the road edge but not at 60 feet from the road centerline. The pines on symptomatic sites at 20 feet from the road showed foliage concentrations of chloride high enough to cause injury. A similar trend was found in the soil with a significant difference in the concentration of all three ions with respect to distance. While sodium and magnesium decreased with distance, chloride increased. Although there was a significant difference between soil amounts of these three ions at 20 feet and 60 feet, the amounts at all sites were too low to result in injury to the trees, pointing to aerial spray being the vector of the ion into the trees. Ozone injury was investigated as a possible additional stressor for these trees. Active and passive ozone monitors were deployed for two years along state highways in the Black Hills to quantify ozone concentrations and determine if this pollutant may have been responsible for the discoloration observed in foliage. Ozone concentrations were not sufficient to be a contributing factor in the decline of roadside ponderosa pine trees. While deicing salts were a primary stress, it appears that the drought that occurred during much of the past decade was a contributing factor in pine discoloration and decline.

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TABLE OF ACRONYMS

Acronym	Definition
ADT	Average Daily Traffic
ANOVA	Analysis of Variance
BHNF	Black Hills National Forest
Ca^{2+}	Calcium ion
$CaCl_2$	Calcium Chloride
Cl^-	Chloride ion
DBH	Diameter Breast Height
EPA	Environmental Protection Agency
GIS	Geographical Information System
GLM	General Linear Model
GPS	Global Positioning System
meq	milliequivalents (molar equivalents x 10^{-3})
mg	milligram
Mg^{2+}	Magnesium ion
$MgCl_2$	Magnesium Chloride
N	Size of the sample population
NAAQS	National Ambient Air Quality Standard
Na^+	Sodium Ion
NaCl	Sodium Chloride
NIST	National Institute of Standards & Technology
NO_x	Nitrogen oxide (various)
NO_2	Nitrite ion
NO_3	Nitrate ion
NPS	Non-point Source
O^{2+}	Oxygen ion
O_3	Ozone
ppb	parts per billion
ppbv	parts per billion by volume
ppm	parts per million
SAR	Sodium absorption ratio
SDCL	South Dakota Codified Law
SDDOT	South Dakota Department of Transportation
SDSU	South Dakota State University
SE	Standard Error
USDA	United States Department of Agriculture
USGS	United States Geological Survey
VOC	Volatile Organic Compounds

1. EXECUTIVE SUMMARY

Chloride and metal ions contained in deicing salt aerial spray and runoff have been associated with damage to roadside vegetation and soil contamination for more than forty years in the United States and other northern temperate zone countries. The widespread appearance of discolored foliage and canopy dieback in ponderosa pines (*Pinus ponderosa*) along the state highways in the Black Hills of South Dakota in 2005 was attributed by some members of the public to deicing salt applications.

1.1. Objectives

The goal of this project was to define the extent and distribution of discoloration and dieback in roadside pines and determine if road deicing salts may be contributing to the poor appearance of the trees. If road deicing salts were considered to be a causal agent in the decline, recommendation would be provided to the SDDOT to reduce exposure and damage.

1.2. Identify tree damage and contributing factors

Define the extent, distribution, sources and contributing factors involved in the damage to the pine adjacent to highways in the Black Hills.

1.2.1. Roadside Vegetation Surveys

The extent of discoloration and dieback in roadside pines was determined through two vegetation surveys (2007, 2011) of all trees within 60 feet of the road centerline. At one-mile intervals along the highways, data was collected on the presence or absence of trees and, where trees were present, the composition of the trees—either deciduous or pines—and finally, if the vegetation was pine, the discoloration and dieback of the canopy.

The roadside vegetation surveys covered 346 miles of roads. Trees were within 60 feet of the road centerline at 225 points, approximately 60 percent of the total. Ponderosa pine was the most common species found at these points, occurring at all but three percent of the points with trees. The ponderosa pines on approximately three-fourths of these points presenting no or minimal (less than five percent) dieback during the 2007 survey. Only five percent of these points had pines presenting moderate (15 to 30 percent) dieback. No points had pine trees exhibiting more than 30 percent dieback.

Ponderosa pines on only about one-fourth of the observation points presented less than five percent dieback during the 2011 survey, a substantial decrease from the earlier survey. There was also an increase in the points with trees presenting between five and 15 percent crown dieback. It would be unlikely to see an improvement in pine trees presenting more than five percent dieback over this short time period, as the dieback is an accumulative process on conifers such as pines. Branches that die back on conifers (e.g. pines) cannot generate new shoots and will remain bare until overgrown by unaffected shoots. Since canopy dieback will remain visible for many years even as the tree recovers it is a better indicator of the accumulation of past stresses than of current conditions. The dieback observed in 2011 was a reflection of the accumulation of stress during previous decade, rather than the severity of a stress event in 2011.

Foliage color is a better measure of the current health of a canopy. Ponderosa pine normal foliage color is generally a dark gray green, which is the source of the name for the region, the Black Hills. The foliage color of trees was a normal dark gray-green on only about one-fifth of the points in the 2007 survey, but this increased to almost two-thirds of the points by the 2011 survey. The change in color from a light green or yellow-green to a dark gray-green indicates a recent reduction in stress. The two surveys indicate that a substantial number of pines along the highways were presenting symptoms of stress. However, by the 2011 survey the condition of the canopies was improving as demonstrated by the increase in trees with the normal dark gray-green foliage.

1.2.2. Investigation of Deicing Salts in Soils and Pine Foliage

Four locations along the state highways with roadside ponderosa pines presenting symptoms associated with deicing salt applications (yellowing foliage and branch dieback) were paired with four nearby locations with asymptomatic trees. Soil samples were taken on both sides of the road at three measured intervals, three and 20 feet from the edge of the pavement and 60 feet from the road centerline. Foliage samples were collected from the pine closest to the 20- and 60-foot sampling points, there being no trees at 3 feet from the pavement edge. The soil and foliage samples were analyzed for the presence of chloride (Cl^-), magnesium (Mg^{2+}), and sodium (Na^+) ions, all common components of deicing salts. The soils and foliage on these sites were sampled during four periods, autumn 2006, spring 2007, autumn 2008, and spring 2008.

The only trees with sodium foliage concentrations greater than 0.2 percent dry weight, the threshold for injury to foliage, for any of the sampling periods were three of the four pines at 20 feet from the pavement edge on upslope symptomatic sites. Chloride foliage concentrations high enough to cause injury were found only on pines at symptomatic sites. The ponderosa pines at approximately 20 feet from the road edge and on the upslope side of the road had foliage concentration of at least 0.4 percent dry weight (the threshold for injury) of chloride during at least one of the sampling times. The upslope side of the road was also the east or south side of the road and the dominant March and April winds are from the north and west. This results in traffic carrying dried salt dust from the road surface into the canopies of the trees on the east and south side of the road. Magnesium concentrations were only slightly higher than normal and only on the trees at 20 feet from the pavement edge, with no difference between trees on symptomatic and asymptomatic sites at 20 or 60 feet.

The highest mean foliage concentrations of sodium and chloride were found in the spring sampling (2007 and 2008) and the lowest in the autumn sampling (2006 and 2007) for symptomatic pines at 20 feet from the road edge, though there was not a statistically significant difference between the two seasons for any ions. Salts do not accumulate in pine foliage from season to season unless soil concentration of these ions are very high.

Salt absorption into needles does not occur until air temperatures exceed 36ºF. Uptake increases in the spring as the temperatures reach 60ºF. Temperatures above freezing are common in the Black Hills during late winter, so some uptake may occur during this period, though the peak of absorption most likely occurs during the warm days in March and April. If high precipitation occurs during this time of year or later into May and June, much of the salt washes from the needles before being absorbed. Spring precipitation will also wash the dried deicing salts from the road surface.

The soils at three feet of the road edge contained the highest concentrations of sodium and magnesium. Concentrations decreased as the distance from the road increased. The concentrations at three feet from the edge of the road were higher than what is common in the region’s soils. Soil sodium concentrations at three feet from the road edge were high enough to result in injury to pine, particularly seedlings. The sodium concentrations at 20 feet, while not high enough to injury pine, were still higher than at 60 feet, where the amounts were near normal. There was a significant difference in the mean extractible soil sodium concentrations between soil samples taken pines at 20 feet on asymptomatic and symptomatic sites. This difference mirrors that of the foliage where there was also a significant difference in the mean sodium foliage between pines on asymptomatic and symptomatic sites. The concentrations present in the foliage of pines at 20 feet, even symptomatic sites, were generally too low to result in injury to the canopy.

Mean soil magnesium concentrations also showed a significant difference with respect to distance from the road. However, no soil sample collected at any location or depth was sufficient to reach levels that were above that identified as even moderate in regards to soil fertility. As with sodium, there was a significant difference between the means of extractible magnesium content in soil at 20 feet between asymptomatic and symptomatic sites. Chloride, the deicing salt ion most associated with plant injury, also varied with distance, but the concentration increased with distance with higher amounts on the downslope than the upslope. The increased chloride concentration on the downslope was due to the increased permeability of channery soils, which allows the chloride ion to move quickly.

The occurrence of higher chloride and sodium foliage concentrations in the trees on the upslope and downwind side of the road, while soil chloride and sodium had the opposite trend indicates that the vector for salt movement was aerial spray of deicing salt droplets or deicing salt dust from the road surface, rather than through soil via runoff from the road. The dominant factors determining the amount of chloride that enters through the foliage are the amount of chloride placed on the road in deicing operations, the volume and speed of traffic, and precipitation amounts during spring and early summer. High-speed traffic can lift dried salt farther into the air. Low precipitation allows more chloride to dry on the pavement as dust and later be carried into the canopies. Once deposited on the foliage, the chloride remains to be absorbed rather than washed off during a rain.

1.2.3. Ozone Investigation

Ozone was investigated as a contributor for the foliage discoloration and canopy dieback of the ponderosa pines. Ozone, a secondary pollutant caused by the action of ultraviolet radiation in sunlight on hydrocarbons and oxides of nitrogen, is a major abiotic stressor associated with declining ponderosa pines in the western United States. During the summer of 2008 and 2009 sites along state highways were chosen for installation of passive ozone monitors based upon the appearance of pines with discolored, particularly mottled, foliage, common symptoms of ozone. Site locations for passive and active ozone monitors were changed from 2008 to 2009 to allow for monitoring regional air-shed ozone. In addition, the 2009 ozone study was set up to monitor ozone concentrations within the canopy of pines. Analysis revealed that June and July had several peaks in the “ozone damaging" range, but no prolonged high ozone levels occurred. The levels of ozone in the area were not high enough in 2008 or 2009 to be responsible for the foliar symptoms on ponderosa pine foliage.

1.2.4. Drought

Symptoms of deicing salt injury on pines presents as foliage discoloration and branch dieback in the lower canopy and along the side facing the highway. The affected needles are often yellow at the tips with an abrupt transition between the dead and green portion. Many of the pine trees identified as symptomatic also exhibited discolored foliage and dieback in the upper canopy. The symptoms of drought on pines begin in the upper canopy and the outer branch tips and gradually spread lower in the canopy and into the interior as the drought persists. Pines affected by drought also will have early senescence and abscission of the needles with many needles shedding prematurely.

The Black Hills experienced a drought during much of the mid-2000s with normal spring and early summer precipitation only returning in 2008. It appears that the drought played a significant role in the poor appearance of the pines along the highways of the Black Hills. May and June are generally the wettest months of the year in the Black Hills and may account for one-third of the total annual precipitation. Ponderosa pine shoot and needle expansion occurs during this same period. Moisture stress during foliage expansion is expressed by yellowing needles, particularly the older needles. The April through June precipitation from 2004 to 2007 was about 70 percent of the long-term average with 2008 to 2010 being normal or above normal. The foliage color of the roadside pines improved from the 2007 to the 2011 road surveys.

1.3. Support Maintenance Practice Decisions

Provide the South Dakota Department of Transportation (SDDOT) with the scientific data to either maintain current road deicing practices or modify practices to minimize impact to roadside trees.

1.3.1. Interviews to Review Current SDDOT Deicing Procedures

Interviews were conducted with SDDOT staff to acquire knowledge of the Black Hills highway network and current SDDOT deicing procedures. The primary deicing salt used by the SDDOT during the study sampling period (2006-2008) was sodium chloride blended with sand. The rate for application for this blend was approximately 100 to 300 pounds per lane mile. Along curves, on bridges or stretches of roads that were shaded for long times during the day, crews applied the salt/sand blend at rates up to about 800 pounds per lane-mile. Vehicles dispersing the blend were not to exceed 15 to 30 mph.

This blend was sometimes pre-wetted with a 30 percent liquid solution of magnesium chloride. The solution was sprayed on the sodium chloride and sand blend as it left the spreader and was applied at the rate of approximately six gallons of solution per lane mile.

1.3.2. Determine the current Procedures Impact

The deicing practices current at the time of the study were a contributing factor in the decline of the roadside pines. Recommendations on deicing practices were made to reduce the contribution road deicing salts have on the appearance and health of roadside pines.

1.4. Summary of Findings

The discoloration and dieback of pines along the state highways in the Black Hills were due to two stress agents, road deicing salt and drought. Concentrations of deicing salts, specifically chloride, were high enough in the foliage of the symptomatic pines at 20 feet from the pavement edge to cause discoloration and dieback of these trees. However, since the appearance of many trees on the symptomatic sites improved by the conclusion of the study, the most likely predisposing stress agent was the drought that ended in 2008. The trees' symptom response to these two stressors is similar and the two in combination can create more injury than either one alone. The low precipitation also aided in the deposit and absorption of salt into the trees. Salt that dries on the pavement is dislodged by the tire-road interface and updrafts generated by the vehicular traffic causes redistribution of the deicer into the canopies of trees. The dry deposition of the aerosol results in foliage injury due to the direct uptake of chloride into the needles.

1.5. Recommendations

Based upon the findings of this study, SDDOT should consider four recommendations.

1.5.1. Track Deicer Use

SDDOT should develop mechanisms to report and track deicing salt use data by unit, snow route, and truck.

Rapid City and Custer units of SDDOT were unable to provide accurate documentation regarding the quantity of deicing salts they applied during the study period. We recommend that the SDDOT adopt a deicing salt dispersal system for their vehicles that can monitor and quantify the amounts of deicing salt used. This will be a very valuable means of measuring the reduction in salt use on the roads and more accurately adjusting application rates to road condition.

The South Dakota Department of Transportation lead a multi-state pooled fund study that was completed in 2012, after the data collection of this study was completed. The MDSS uses time- and location-specific weather forecasts and computer modeling of weather, pavement, traffic, and maintenance to optimize the type and timing of winter maintenance treatments. Snowplows are equipped with instrumentation that tracks vehicle location, measures air and road temperature, and reports operators' visual observations of road condition, plowing activity and the type and application rate of deicing material applied to the roadway. The adoption of automatic vehicle location (AVL)/ global positioning system (GPS) is a key component of MDSS. The implementation of MDSS by the Indiana Department of Transportation during one winter resulted in a reduction of 228,470 tons of salt, about 40 percent less deicing salts from the previous year (McClellan et al., 2009).

The deployment of the AVL/GPS which monitors weather/road conditions and salt applications as part of the MDSS fulfill this recommendation.

1.5.2. Reduce Chloride Use

SDDOT should reduce the use of chloride along roadways in the Black Hills.

Ponderosa pine is the dominant species in the Black Hills forest and the most common tree found along the highways. It is also the most sensitive of the native trees to deicing salts and the only species in which we saw injury. The roadways that have ponderosa pines within 60 feet of the centerline is where the reduction in deicing salts is needed. This is about two-thirds of the roadway length in the Black Hills.

Chloride is the component in deicing agents responsible for vegetation injury and any delivery system that reduces the amount applied on the roads will be beneficial to the health and appearance of the roadside vegetation. Chloride reduction can be accomplished by reducing the amount of chloride used in deicing operations, using direct liquid applications of deicing salts, and pre-wetting dry deicing materials as they are applied to the roadway. Direct application of salt brine, rather than a solid, can reduce chloride applications rates by half (Fay, et. al., 2013). Pre-wetting can increase the performance and retention of solid chemicals and abrasives on the pavement and reduce chloride applications rates by 10 percent (O'Keefe and Shi, 2006).

Since the completion of this study, the SDDOT has switched from using a salt/sand mixture to salt and a salt brine. They are also using liquid magnesium chloride in select locations. These practices fulfill this recommendation.

1.5.3. Reduce Winter Speed Limits

SDDOT should consider reducing winter driving speed limits in the Black Hills.

The amount of chloride carried into the ponderosa pine canopies and absorbed by the foliage depends on the application amount, the precipitation during late winter to late spring, and the volume and speed of the traffic. Only two factors—the amount of chloride applied and the speed of the traffic—lie within the control of the SDDOT. Updrafts generated by vehicular traffic redistribute deicing agents into the environment beyond the road. Highway speeds between 50 and 55 miles per hour have been shown to carry deicing salts to distances of 15 to 25 feet from the pavement edge. We were able to find foliage injury due to chloride concentration on the pines at 20 feet on symptomatic sites. Reducing the speed of the traffic can reduce the distance of potential plant damage (Blomqvist and Johansson, 1999). While relatively few studies have investigated vehicular speed and deicing salts, a reduction from 55 to 40 miles per hour could possibly reduce the amount of road salt carried beyond the pavement by one-third.

This reduction would be only along lengths of roadway that have ponderosa pines within 60 feet of the road centerline. This is about two-thirds of the road system.

1.5.4. Maintain Trees near the Roadway

SDDOT should, wherever possible, maintain trees at 30 feet from the pavement edge in the Black Hills

The mountain pine beetle (*Dendroctonus ponderosae*) epidemic in the Black Hills resulted in thousands of acres of dead ponderosa pines. Infested and dead trees within 60 feet of the highway were a fall hazard to traffic and most of these trees have been removed. The USDA Forest Service also increased thinning programs on the lands they managed to reduce the susceptibility to mountain pine beetle attack. The result of these efforts is a decrease in pines within 60 feet of the road during the 2010s. The highest concentrations of deicing salts in our study were found at three feet from the edge of the road and concentrations of ions in the foliage and in the soil significantly decreased at 20 feet and were within the normal ranges by 60 feet. Several deicing studies have noted that the distance of injury increases in open meadows compared to dense forests (Hofstra and Hall, 1971). Maintaining tree cover at 30 feet from the road may reduce injury farther into the forest. We encourage maintaining healthy mature pines within this area to limit the potential spread of salt farther into the environment.

2. PROBLEM STATEMENT

During the early 2000s, concern arose from the public regarding the poor appearance and dieback of pines along the highways in the Black Hills of South Dakota. Callers to the South Dakota Department of Agriculture (SDDOA) wondered why the pines along highways appeared to be dying in large numbers. The primary suspect was deicing salt due to the proximity of the declining pines to the road. Deicing salt is a frequent stressor of trees, particularly conifers, along roads and highways.

Tree dieback and discoloration have been associated with the application of deicing salt since the 1950s (French, 1959). Numerous studies have linked roadside woody plant vegetation injury to deicing salt exposure (Hofstra and Hall, 1971; Emmons et al., 1976; Hagle, 2002). The most common symptom associated with deicing salts is browning foliage, beginning at the tips or margins, and progressing to the base of the leaf or needle (Sinclair and Lyon, 2005). Affected foliage may also abscise prematurely. This foliar symptom is more common on conifers, as they normally retain needles for several years so the premature loss of the older foliage is very noticeable (Barrick et al., 1979). The dieback of branches in the canopy affected by deicing salts generally occurs on the side facing the road and along the lower canopy (Sinclair and Lyon, 2005).

The deicing salt most widely used by the South Dakota Department of Transportation (SDDOT) on highways in the Black Hills during the time period of this study was sodium chloride (NaCl) blended with sand. Sodium chloride, otherwise known as rock salt, is historically the primary deicing chemical preferred by state departments of transportation. The main reasons for its popularity are low cost and the ease with which it is stored, distributed, and handled. Sodium chloride is an effective deicer at temperatures above 10°F and readily dissolves into sodium (Na^+) and chloride (Cl^-) ions forming salt brine that exhibits lower freezing temperatures than water (Gales and VanderMeulen, 1992). Another salt, magnesium chloride ($MgCl_2$), was also used by the SDDOT, though far less than sodium chloride. Magnesium chloride as a pre-wetting agent was sprayed as a 30 percent liquid solution on the sodium chloride and sand blend as the material left the spreader.

While sodium and magnesium are common components of deicing salts, the choice of cation does not play a significant role in the severity of plant injury. The toxicity is primarily due to the chloride anion (Hofstra and Hall, 1971; Spotts et al., 1972; Dirr, 1976; Hofstra et al., 1979; Simini and Leone, 1986; Viskari and Karenlampi, 2000). Magnesium is an essential nutrient for tree growth and there is more concern with soil deficiency than toxicity (Harris et al., 2004). While sodium is not an essential nutrient for tree growth, excessive amounts of sodium are rarely toxic except to seedlings. The indirect negative effects sodium has on soil structure and chemistry are more harmful (Frenkel et al., 1978). The sodium ion in deicing salts may replace calcium and other ions in the soil, raise the soil pH, and restrict the availability of micro-nutrients such as iron and manganese to the tree.

Chlorine, though an essential micro-nutrient for tree growth, is more likely to be toxic than deficient in its ionic form, chloride (Cl^-) (Harris et al., 2004). Chloride ions accumulate in needles, buds, shoots, and trunks, either from root absorption or from roadside spray or aerosol collecting on foliage. The chloride is carried to the tips of shoots and needles where it accumulates to damaging levels. The extent of injury depends upon the species' tolerance to absorbed chloride ions and its ability to retard accumulation of this ion (Sinclair and Lyon, 2005). The degree to which internal chloride concentration can injure trees depends on several other factors, including whether the trees are stressed by drought or unseasonably warm temperatures in late winter. Warm late winter and early spring temperatures can intensify chloride ion uptake. Under such conditions, salt concentrations are higher in older overwintering needles than in those of new foliage that emerges later in May (Viskari and Karenlampi, 2000; Emmons et al., 1976). Foliar concentrations tend to peak in late winter, plateau in spring, and decline throughout the summer, reaching their lowest concentrations in autumn (Hanes et al., 1976).

Two avenues, absorption either through the roots or foliage, allow chloride and metal ions to enter the tree. Deicing salts may be transported via precipitation runoff from the roadside into the surrounding soils where the ions are absorbed by the tree's root system. The rate at which salt ions run off the road and seep into the soil is affected by several factors, including the slope and drainage of the terrain, the amount of salt used, and various soil properties including infiltration rates, permeability, structure, porosity, humus level, cation exchange capacity, and texture.

Aerial transportation has two distinct categories, splash or spray. Splash occurs during the winter as slush containing the deicing salt is carried to the edge of the pavement by the traffic. Generally, splash results in injury close to the road edge whereas spray, fine droplets and dust particles, are carried through the air much farther. Aerial spray occurs when fine droplets or dust particles of salt are carried by winds some distance from the roadway itself, whereas traffic splash occurs when salt brine is sprayed from vehicles directly on adjacent vegetation (Lumis et al., 1976). Droplets form when the salt brine is carried as an aerosol mist by updrafts from vehicles driving over the wet surface. Salt can also dry on the pavement and then be lifted by updrafts created by motor vehicles and carried farther by the wind as a dust (Cunningham et al., 2007). Plant injury due to salt being transported as a droplet or dust is most commonly seen on the downwind side of the road (Hofstra and Hall, 1971). The greatest vegetative damage due to aerial salt spray occurs to vegetation growing within 100 feet of the roadside edge (Hofstra and Hall, 1971; Viskari and Karenlampi, 2000; Hagle, 2002). However, some studies have identified tree injury from aerial salt spray as far as 1,300 feet from the road (Fromm, 1982; Blomqvist and Johansson, 1999).

While deicing salts have been associated with injury to roadside trees, it is not the only stressor to these trees. Numerous other abiotic stressors can result in discolored foliage and canopy dieback. Drought and ozone are common pine stressors in the western United States that can result in discolored foliage and dieback, though their symptoms may differ from those due to deicing salts. Salt accumulation and drought stress on conifers cause discoloration of the needles, with the tips usually turning yellow first. While needle discoloration presents for both stresses, the location of this discoloration in the canopy differs. Salt accumulation occurs over the canopy facing the road or the lower canopy, but with drought stress, the symptoms first present at the top of the tree. Drought and deicing salt stresses combined create even more injury then either agent alone (Sucoff, 1975). Low spring precipitation can result in salt remaining on the foliage or on the roadway longer, increasing the exposure time.

Ozone is another major stressor damaging to conifers, particularly pines. Ponderosa pine is one of the species most sensitive to ozone and foliage injury may occur at ozone concentrations greater than 60 ppb (Campbell et al., 2000). The symptoms of exposure to high concentrations of ozone are similar to those expressed from deicing salts, with some differences. Ozone affects foliage cells in a non-random fashion causing a mottling effect as it destroys mesophyll cells under the leaf or needle surface, usually without causing extensive harm to the surface itself (Miller, 1996). This results in flecks of yellow along the length of the needle rather than yellowing at the tip. Tree dieback and death will also occur with long-term exposure to high levels of ozone. The canopy dieback pattern for ozone stress is similar to that occurring with deicing salts with the mortality beginning on the lower branches and progressing to the top (Miller et al., 1963). Ozone levels are often higher during dry, hot summers, a common occurrence during the 2000s, and ozone levels greater than 60 ppb were recorded at Wind Cave National Park near Hot Springs, South Dakota during his time period.

Several biotic stressors, mountain pine beetle and two pine diseases, cause foliage discoloration and dieback in pines though their presentation differs and not commonly confused with deicing salt injury. Mountain pine beetle is a bark beetle common throughout western North America. The insect periodically enters an epidemic phase where tree mortality can reach more than fifty percent. The epidemic in the Black Hills began in 1997 and continued until 2015. The initial canopy symptom of trees infested by mountain pine beetle is yellow foliage. This foliage turns red to brown the following year before turning gray and falling.

Elytroderma needle cast fungus (*Elytroderma deformans*) causes affected needles to turn yellow beginning at the tips and progressing down. Infected needles often abscise prematurely resulting in retention of only the current year's needles. Trees infected by elytroderma needle cast can also be identified by the presence of large witches-brooms, tightly packed clusters of stunted branches, in the canopy (Sharpf, 1993).

Diplodia tip blight (*Diplodia pinea*) is a common twig and foliage disease of pine in the Black Hills. Infected shoots become stunted and exhibit yellowing needles that eventually hang and turn an ash-gray. The disease symptoms are commonly expressed after a hail storm as the mechanical injury further stresses the tree and allows the fungus to proliferate. It is a common sight in the Black Hills to see large pockets, often 50 trees or more, all showing symptoms of the disease. Numerous pines along US16 between Rapid City and Rockerville, South Dakota exhibited yellowing foliage from infection by this disease.

3. OBJECTIVES

The purpose of this research was to determine the effects of deicing salt application on roadside pines in the Black Hills of South Dakota and the extent of damage with respect to the surrounding forest trees and soils. Determining the effects on roadside pines and soils due to deicing practices provided a critical baseline for evaluating the consequences of continuing current practices and offered insights into possible modifications of maintenance activities in the Black Hills.

The project's defined objectives were to:

3.1. Identify tree damage and contributing factors

Define the extent, distribution, sources, and contributing factors involved in roadside tree damage and injury adjacent to highways in the Black Hills.

This objective was accomplished by:

3.1.1 Roadside vegetation survey

A survey of the extent of discoloration and decline roadside pines was conducted along state highways in the Black Hills of South Dakota in 2007 and repeated in 2011. Observation points were established at one-mile intervals and the following information recorded: point location, presence or absence of trees within 60 feet of the centerline of the road, and if trees occurred, their species and condition as defined by the percentage of dieback and needle discoloration.

3.1.2 Investigation of Deicing Salts in Soil and Pine Foliage

Roadside sites with ponderosa pines presenting symptoms of exposure to deicing salts (symptomatic sites) were identified and paired with nearby sites that had pines not presenting symptoms associated with deicing salt exposure (asymptomatic sites). Soil samples were collected at these sites at 3 and 20 feet from the road edge and 60 feet from the road centerline. These samples analyzed for extractable chloride (Cl^-), magnesium (Mg^{2+}), and sodium (Na^+), pH, sodium absorption ratio, and texture. Needles from symptomatic and asymptomatic pines at 20 feet from the pavement edge and 60 feet from the road centerline were analyzed for their chloride, magnesium, and sodium content.

3.1.3 Ozone Investigation

Ozone monitoring was conducted to determine if the concentration exceeded the levels associated with injury to ponderosa pines. Active and passive ozone monitors were deployed in 2008 and 2009. In 2008 monitors were positioned to obtain regional air-shed ozone data. In 2009 ozone was monitored within the canopies of individual trees.

3.1.4 Drought

The symptoms of drought can mimic those from deicing salts and drought can increase salt injury to trees. Spring and early summer precipitation data was collected for the time period of the study to determine if drought conditions were present.

3.2. Support Maintenance Practice Decisions

Provide the South Dakota Department of Transportation (SDDOT) with the scientific data to either maintain current road deicing practices or modify practices to minimize impact to roadside trees.

This objective was accomplished by:

1) Interviews were conducted with SDDOT staff to acquire knowledge of the Black Hills highway network and current SDDOT deicing procedures.
2) The foliage and soils data identified as part 2 of Objective 1 provided data as to the current deicing applications' possible impact on roadside trees.

4. TASK DESCRIPTION

The following tasks (Table 4.1) were identified for completion of this project. There were several adjustments made to the selection of tasks and the order in which they were performed during this study. These changes are discussed below.

Table 4-1. SDDOT and SDSU Task Organization.

#	SDDOT Research Project Statement	SDSU Proposal April 2006	Final Report
1	Literature Review	Literature Review	Literature Review
2	Meet with technical panel	SDDOT staff interview	Selection of sites to investigate deicing salts in soils and pine foliage
3	SDDOT staff interviews	Selection of sampling sites	Conduct first sampling of soils and foliage for chloride, magnesium and sodium
4	Survey researchers/states	Conduct first sampling of soils and foliage for chloride, magnesium and sodium	Conduct second sampling
5	Create testing matrix	Conduct second sampling	Meeting with technical panel
6	Sampling and testing	Meeting with technical panel	SDDOT staff interview
7	Field trip with technical panel	Conduct sampling of snowpack for chloride	Survey of the condition of pines along state highways
8	Interim report	Conduct third sampling	Snowpack chloride analysis
9	Additional sampling	Conduct fourth sampling	Conduct third sampling
10	Assessment	Data analysis	Conduct fourth sampling
11	Recommendations	Final report	Ozone testing
12	Final report	Executive presentation	Data analysis
13	Executive presentation		Final report
14			Executive presentation

4.1. Task 1: Literature Review

The investigators completed a search of available literature on deicing impacts of roadside woody plants. The search was a computer-based search using the resources at South Dakota State University. Journal articles, books, and conference proceedings identified in the search were retrieved from the library or through their on-line subscription to journals. These papers are referenced in the Problem Statement Section 2 and Findings and Conclusions Section 5.

4.2. Task 2: Selection of sites to investigate deicing salts in soils and pine foliage

A preliminary road survey was made by John Ball and foresters from the South Dakota Department of Agriculture to identify sites for foliage and soils sampling. The final selection of the sites was made by field visits from John Ball, Douglas Malo, and Howard Woodard. Four sites were identified along state highways with ponderosa pines presenting symptoms (needle discoloration and canopy dieback) commonly associated with deicing salt injury that could be paired with locations less than one mile away with asymptomatic pine trees (Figure 4.1). The locations were considered symptomatic if five or more trees exhibiting symptoms consistent with deicing salt exposure were found within 100 feet along the road but no further than 60 feet off the road centerline. These symptoms include one-year old needles turning yellow to brown, generally at the tips continuing toward the base, second and third year needles often being absent, and portions of the canopy exhibiting dieback.

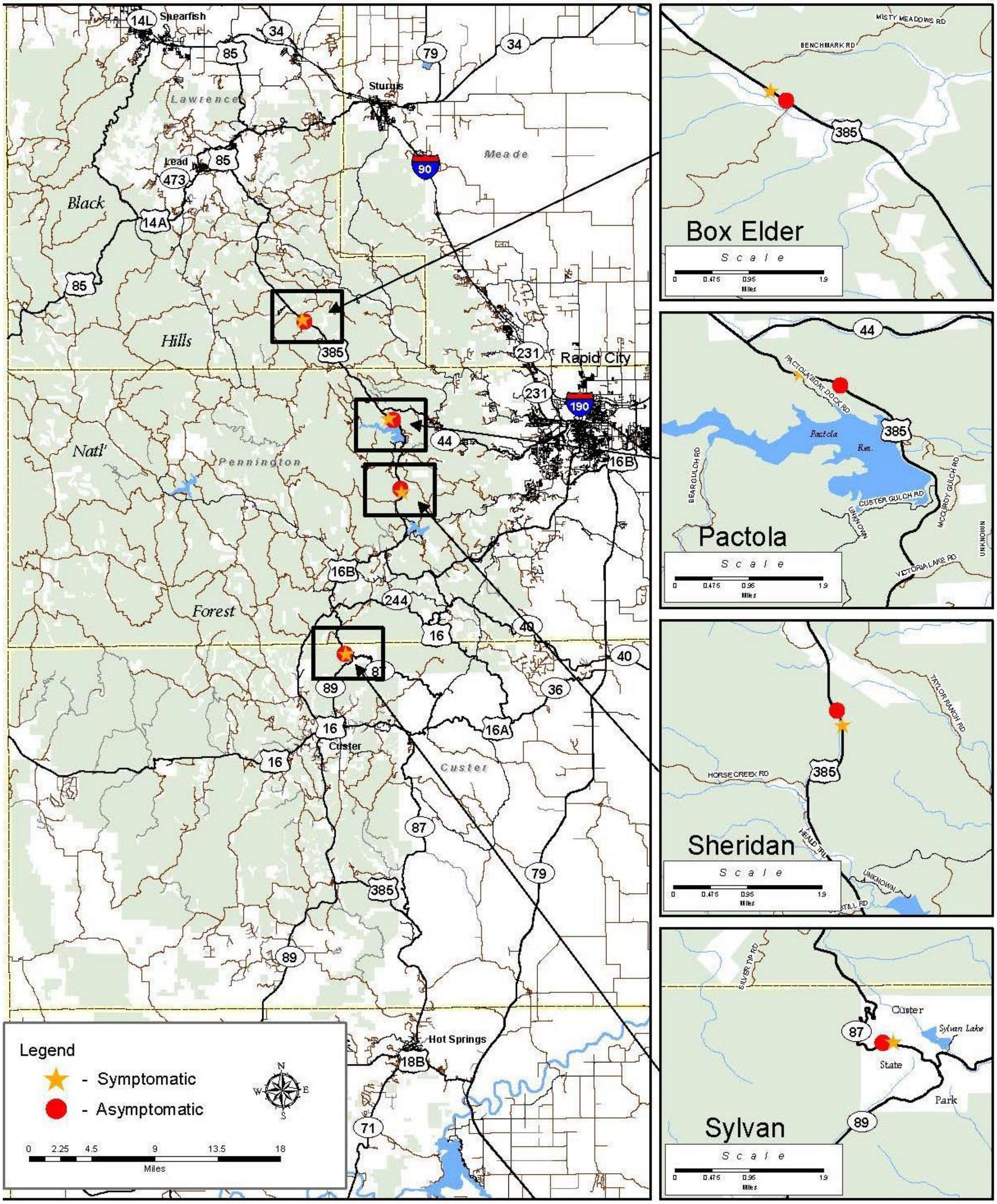

Figure 4-1. Symptomatic and Asymptomatic Sites.

The four sites examined in this study were located on the two main highways in the Black Hills. Three sites were along US385 and numbered 1 through 3 (site names: Box Elder, Pactola, and Sheridan respectively). The fourth site (site 4) was along SD87 (site name: Sylvan) (Table 4-2). At each site, symptomatic trees were paired with a nearby location with asymptomatic trees. The paired locations were within close proximity, less than one mile apart, and the trees were similar in height and diameter. The only difference between the trees on these paired locations was the presence or absence of canopy symptoms associated with the application of deicing salts. Regardless of whether the location was identified as having asymptomatic or symptomatic trees, the trees more than about 30 feet from the pavement edge were not presenting foliage discoloration or canopy dieback at any site.

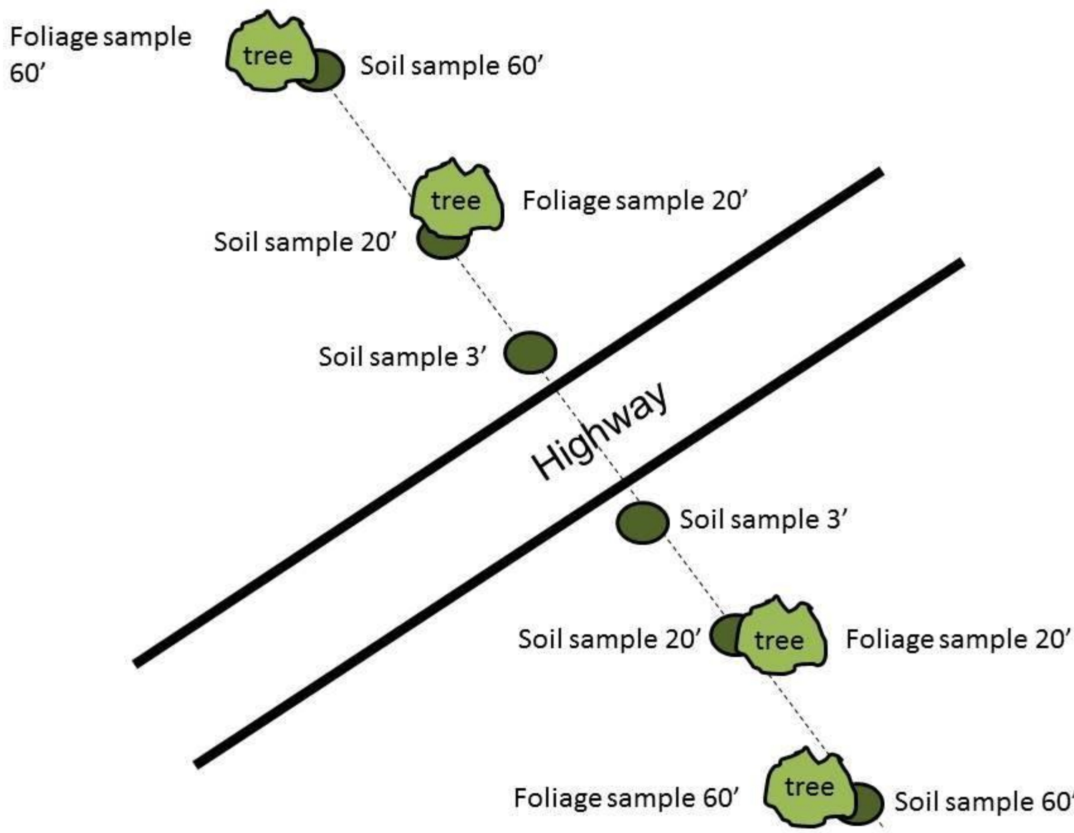

Figure 4-2. Plan for collection of foliage and soil samples at each location at a site.

Table 4-2. Site Locations.

Site #	Site name	Highway	Symptomatic	Latitude	Longitude
1	Box Elder	US385	Symptomatic	44.19217832	-103.62959239
			Asymptomatic	44.19045517	-103.62650977
2	Pactola	US385	Symptomatic	44.08990628	-103.50738768
			Asymptomatic	44.08711930	-103.49998713
3	Sheridan	US385	Symptomatic	44.01302746	-103.48901002
			Asymptomatic	44.01557422	-103.49036864
4	Sylvan	SD87	Symptomatic	44.84536996	-103.57157252
			Asymptomatic	43/84523358	-103.57343556

4.3. Task 3: First sampling

Soil and pine needle foliage samples were obtained from both sides of the road at measured intervals during the summer of 2006. Additional site-specific information such as slope, vegetation structure, and soil composition was recorded. The field data was collected by Howard Woodard and a team of graduate students from SDSU. Howard Woodard also supervised the sample preparation at SDSU.

At each sampling site soil samples were collected approximately three feet and 20 feet from the edge of the pavement. A third sample was taken at a distance of 60 feet from the road centerline. Pine foliage was collected from the nearest pine at the 20- and 60-foot sampling points. Collection of samples from each of the paired locations for a site occurred on both sides of the road (Figure 4-2).

Approximately nine ounces of foliage were collected mid-canopy from the outer branches in the canopy of each sample tree using a Forestry pruner. Samples were gathered during the months of May or June and again in August or September. Foliage collections in the spring were from the previous year's needles and provided a basis for comparing how the trees were affected by the deicing salts used during the previous winter. The pine foliage collected in the fall consisted of the current season's summer growth and provided information on salt uptake, storage, and accumulation within the vegetation during the current growing season.

Shovels and soil probes were used to obtain soil samples as well as a Pulaski bar when rocky substrate was encountered. Tools were cleaned of debris and dust between sampling locations on a site. Soil samples were placed into labeled plastic containers in the field and stored in these same containers until analysis. The containers were cleaned between sampling times to avoid contamination. Soil samples were analyzed for extractable soil chloride (Cl^-), sodium (Na^+) and magnesium (Mg^{2+}), pH, sodium absorption ratio, and texture. Approximately two pounds of soil were collected from each sampling site at depths of 0-6 inches, 6-12 inches, and 12-24 inches.

Needle samples were sent to the SDSU Soil Fertility Laboratory for initial analytical preparation. This preparation consisted of drying, grinding, and packaging the foliage samples for ease of analysis and cataloging of information. The pine needles were dried at 130°F for 72 hours with heated forced air. The air was vented outside and not recycled. Following initial drying, the needles were ground with a Wiley Mill and passed through a one millimeter sieve. The sieve was cleaned between uses with distilled water to remove all particles and debris. Ground needles were packaged and labeled before forwarding to the Soil and Plant Analysis Laboratory at the University of Arkansas for further testing. The preparation of samples was supervised by Howard Woodard. Samples were analyzed for the primary damaging agents of concern: chloride, sodium, and magnesium ions.

4.4. Task 4: Second sampling

The second sampling follow the same procedures as the first sampling. It was completed during June 2007 by Howard Woodard and foresters from the South Dakota Department of Agriculture.

4.5. Task 5: Meetings with technical panel

A meeting with Dan Johnston, the technical panel members, and the SDSU investigators, was held in October 2006 in Rapid City to examine the four sites and discuss the data collection procedures. A second meeting with the technical panel was held in Pierre in January 2007 to continue discussion of the data collected to date. It was decided at this meeting to investigate ozone as a possible contributor for the discoloration and dieback of the roadside ponderosa pines since trees exhibiting symptoms commonly associated with ozone injury were observed along the roads.

4.6 Task 6: South Dakota Department of Transportation staff interviews

State highways in the Black Hills of South Dakota are maintained throughout the winter months by SDDOT Maintenance Unit 451 (Sturgis), 452 (Rapid City), 491 (Custer) and 492 (Hot Springs). Interviews were scheduled with SDDOT staff to acquire knowledge of current deicing procedures. Important deicing information included type and quantity of deicing chemical applied as well as dates of application. These interviews were conducted in August 2007 by Chad Taecker. The Sturgis maintenance unit supplied documentation regarding their deicing salt use from 2002 through the spring of 2007. However, they were only able to provide the total amount of deicing salts applied to the highways, not the amount applied along a specific length of a highway or even a specific highway. The Rapid City and Custer maintenance units were unable to provide any documentation concerning dates or application amounts other than a yearly total.

4.7 Task 7: Survey of the condition of pines along highways

Two vegetation survey were completed along Black Hills highways to determine the extent of the discoloration and dieback of pines within 60 feet of the centerline of the road.

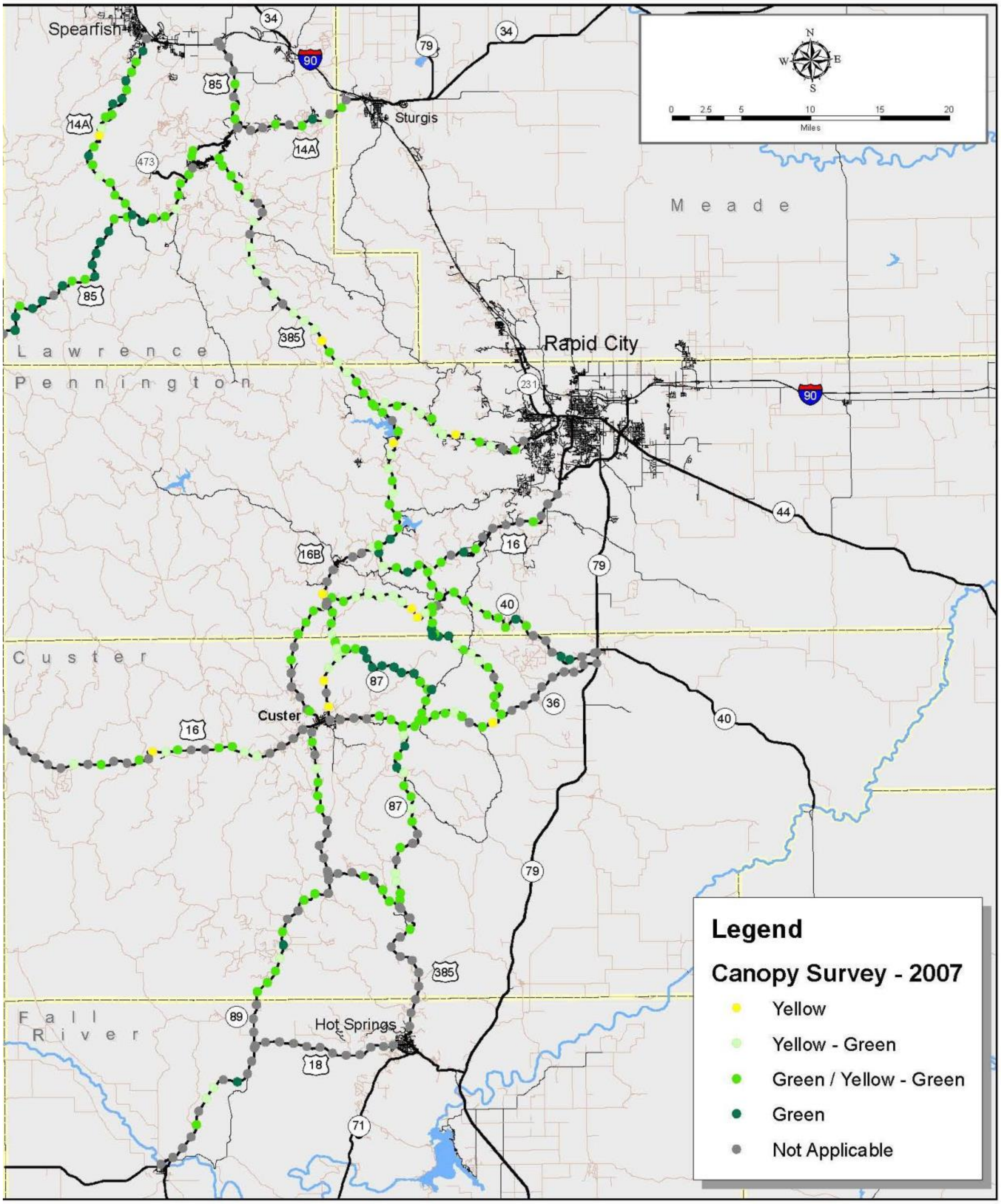

Figure 4-3. 2007 Roadside Vegetation Survey.

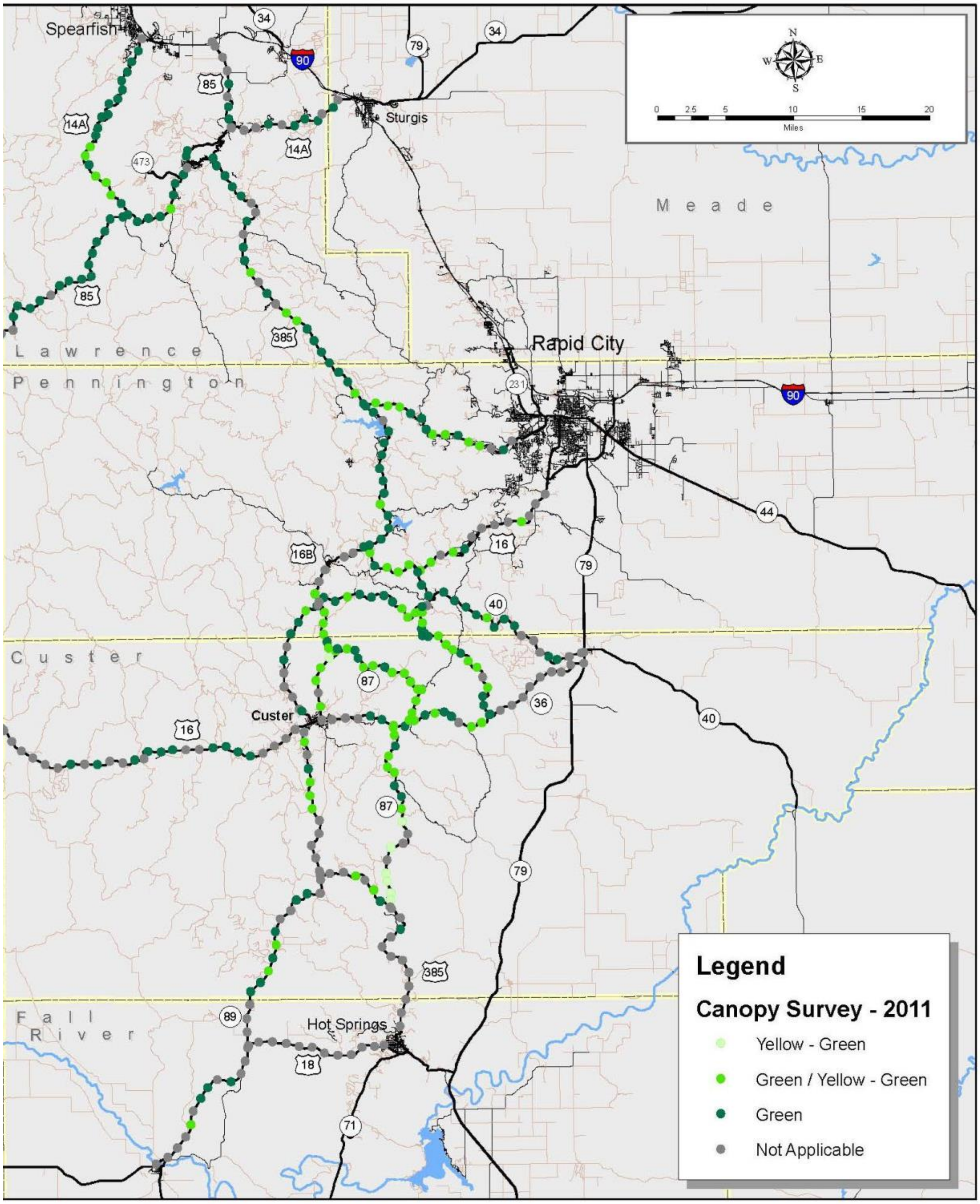

Figure 4-4. 2011 Roadside Vegetation Survey.

The surveys were conducted in 2007 and 2011 along all highways between Spearfish and Edgemont. The survey included US14, US14A, US16, US16A, US18, SD36, SD40, SD44, SD79, US85, SD87, SD244 and US385 (Figure 4-3 and Figure 4-4).

Observation points were established every mile along highways encompassed within the study, excluding segments within city limits, and logged with a Garmin Etrex Vista HCX Global Positioning Device. Locations were overlaid on a geographic information system (GIS) topographic map with additional metadata. Data collected from observation points consisted of:

- identification of the dominant vegetation on the point, either grasses or trees
- if trees were present, tree species either deciduous or coniferous
- if coniferous, either white spruce (*Picea glauca*) or ponderosa pine
- average canopy height
- if ponderosa pine occurred on the point, average crown foliage color and crown dieback

Trees included in an observation point were within 60 feet of the road. Tree height and percent slope of the roadsides were obtained by use of a Suunto clinometer.

Crown condition was evaluated upon two characteristics, foliage color and dieback. The dominant (more than 50 percent of the canopy) ponderosa pine foliage color at the observation points was noted on a scale ranging from gray-green to green (G), green to yellow green (G-YG), yellow-green (YG), yellow (Y), yellow brown (YB), and ash-gray (AG). Dark gray-green to green is the normal color of healthy ponderosa pine foliage. Foliage discoloration, a yellowing, is an indication of stress in pines (Weaver and Stipes, 1990). Brown or ash-gray is the color of dead foliage. Older foliage turns yellow before senescing this natural color change was not considered in the evaluation.

Crown dieback is a measure of crown condition and is based on branch mortality that begins at the terminals and proceeds toward the trunk. Dieback is considered only in the upper and outer portions of the canopies of ponderosa pines; dead branches in the lower canopy are normal and often occur due to shading. Crown dieback followed the classification system created by Keen (1943) (Table 4-3).

Table 4-3. Roadside vegetation survey canopy dieback key (adapted from Keen, 1943).

Damage	Dieback	Description
No Damage	0%	Canopy has no dead branches or twigs beyond what occurs in the lower canopy due to shading.
Minimal	<5%	Less than 5% of the canopy with dead branches. These branches are usually smaller diameter, often second order, and retain their smaller twigs.
Light	5-15%	Between 5 and 15% of the canopy is occupied by dead branches, usually first order. Many of these branches may retain some of their smaller second order branches.
Moderate	15-30%	Between 15 and 30% of the canopy occupied by dead branches. Generally these are larger branches, usually attached to the trunk, devoid of smaller twigs.
Severe	30-50%	Between 30 and 50% of the canopy is occupied by dead branches. These are generally attached to the trunk and are devoid of smaller twigs.
Extreme	>50%	More than 50% of the canopy is occupied by larger diameter dead branches attached to the trunk. The upper trunk is dead and has formed a snag-head.

4.8 Task 8: Snow pack chloride analysis

We intended to measure chloride levels in snow along the roads. However, since there was no data available from the SDDOT Maintenance Units regarding application rates along the sites this task was eliminated.

4.9 Task 9: Third sampling

The third soil and foliage sampling on the paired sites was completed during September 2007. Field sampling was conducted by Chad Taecker and Howard Woodard. Howard Woodard supervised the sample preparation at SDSU.

4.10 Task 10: Fourth sampling

The fourth and final soil and foliage sampling on the paired sites was completed during June 2008. Field sampling conducted by Chad Taecker and Howard Woodard. Howard Woodard supervised the sample preparation at SDSU.

4.11 Task 11: Ozone study

Ozone sampling was conducted with passive and active monitors during both years. Passive samplers operate by collecting ozone using two nitrite-impregnated glass fiber filters. The second filter serves as a backup. The collected O_3 converts nitrite (NO_2^-) to nitrate (NO_3^-) by oxidation. Although the passive monitoring method measures nitrate and not ozone, the nitrate formed from exposure to ozone gives a relative indication of ozone loading among the various sites. The passive monitors used Ogawa sampler badges, each containing two filters, exposed to the air for a period of time, generally two weeks. The two filters from each sampler were collected and mailed to the USDA Forest Service Air Resources Management Laboratory in Fort Collins, Colorado where they were separately extracted and analyzed for nitrate using ion chromatography.

Ozone cannot be accurately calculated from nitrate levels since the loading on the filters varies with temperature, relative humidity, and wind speed. Passive monitors are only used to determine ozone loading regionally and to compare ozone loading among various sites. The nitrate data can be calibrated to the continuous data collected from an active monitor if the two monitors are placed at the same site.

Active monitors, portable battery operated continuous ozone monitors (2B Tech, Boulder, Col.), were installed for both seasons to record actual hourly data. Continuous ozone monitors were calibrated pre- and post-season, and were programmed to auto-zero every three days by pulling intake air through a charcoal filter.

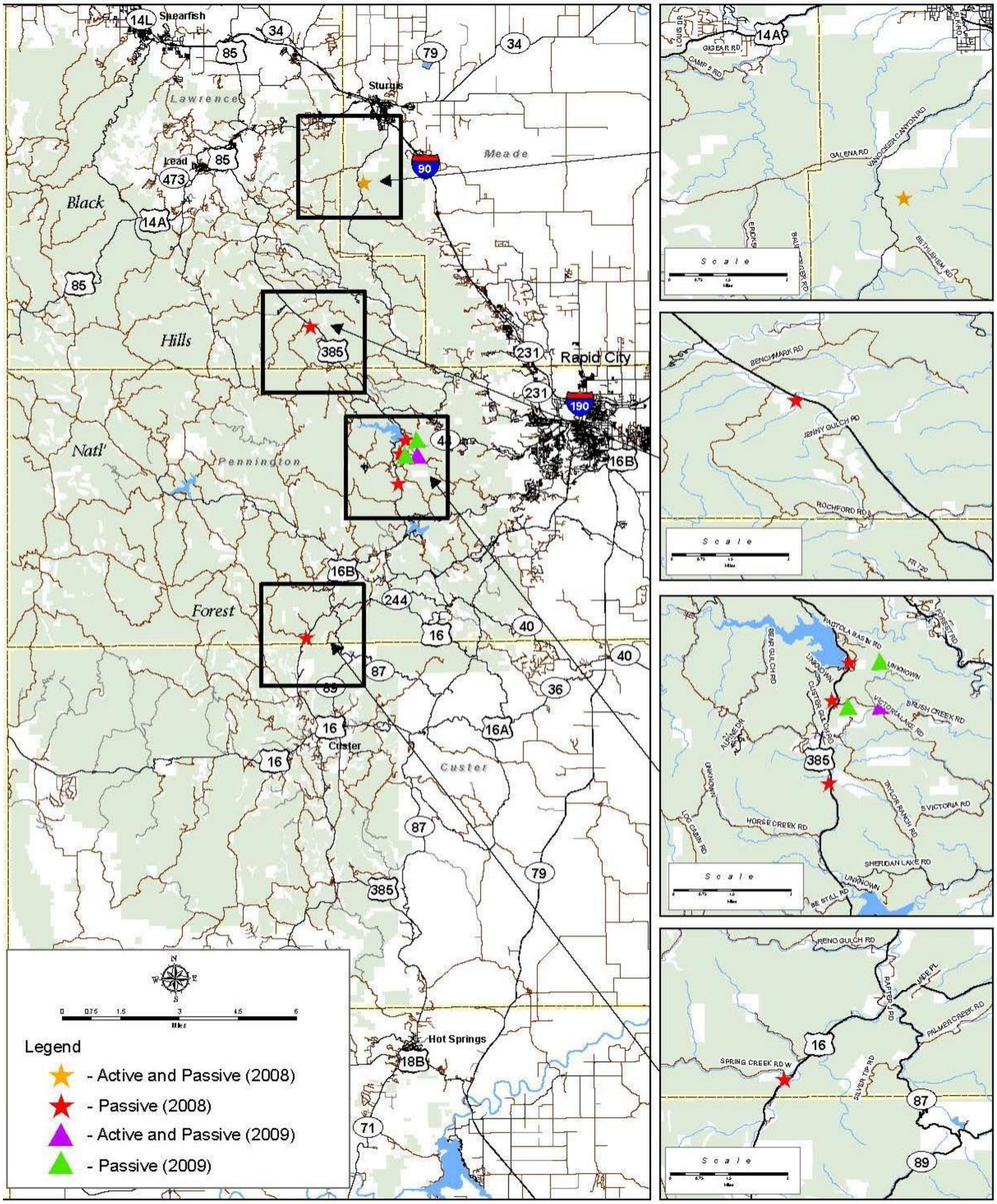

Figure 4-5. Ozone Monitoring Sites in 2008 and 2009.

Data were stored on a Campbell Scientific data logger and the data storage modules were mailed periodically to the USDA Forest Service Air Resources Management Laboratory in Fort Collins, Colorado for analysis. Passive samplers were co-installed with the continuous samplers to determine if the sites had different ozone loading rates compared to other passive ozone sites and to serve as a baseline to relate data from the passive to the continuous monitors.

The monitoring during the 2008 season (May through September) was along US385 in the central Black Hills from just north of the boundary of Lawrence and Pennington Counties to just north of the boundary of Pennington and Custer Counties (Figure 4-5). The selection of the sites was based on large numbers of pines along the US385, particularly near the Pactola Reservoir, that were exhibiting foliage discoloration (Figure 4-5). The specific site selection for placement of the monitors was made by the investigators, John Korfmacher and Robert Musselman, USDA Forest Service research tree physiologists, Dan Johnston from the SDDOT, and Jim Blodgett, USDA Forest Service pathologist and technical panel member, after visits to several potential locations. During early May of 2008 five Ogawa passive ozone sampler badges were deployed at six locations 6.5 feet above ground within 330 feet of US385 to collect ambient air for two-week increments (Table 4-4, Figure 4-5). The active ozone monitor for 2008 was installed near the top of Veterans' Peak northeast of the road where the passive monitors were installed. This active monitoring site off Vanocker Canyon Road was in a semi-forested area with a large northwesterly fetch (Table 4-5. Figure 4-5). A passive monitor was also installed adjacent to the active monitor.

During the 2009 season, monitoring focused on the Pactola Reservoir area along US385 at locations where visible injury symptoms on conifer needles resembling ozone chlorotic banding were observed. The sampler badges were installed within the canopy of a tree at 6.5 feet, 16.4 feet, and 26 feet above the ground (Table 4-5, OZ22-2M, OZ22-5M, and OZ22-8M respectively) at a location near the highway and a single monitor placed in the open about 1000 feet up the hill. Another passive site was located nearby in another tree near the highway at the same three heights (Table 4-5, OZ23-2M, OZ23-5M, and OZ23-8M, respectively). Another single passive monitor was located 110 feet higher and farther from the highway. Sample badges within the tree canopy, and the two open sites, were exposed to ambient air for two-week periods from mid-May through mid-October. Each of the nine two-week exposure periods during the season was assigned a sequential number for comparison among locations. Passive sample badges were removed every two weeks and shipped overnight to the USDA Forest Service Air Resources Management Laboratory in Fort Collins, Colorado for analysis. The location of the active monitor in 2009 was changed to a meadow with an open northerly fetch across from the Pactola Reservoir Visitor Center (Table 4-5, Figure 4-5).

Table 4-4. Passive and active ozone monitoring sites for 2008.

Monitor Label	Monitor Description	Latitude	Longitude
OZ01	Continuous	44° 19' 59"	-103° 32' 20"
OZ02	Passive	44° 11' 04"	-103° 37' 05"
OZ03	Passive	44° 03' 58"	-103° 28' 56"
OZ04	Passive	44° 03' 08"	-103° 29' 28"
OZ05	Passive	44° 03' 17"	-103° 29' 36"
OZ06	Passive	43° 51' 43"	-103° 37' 40"

Table 4-5. Passive and active ozone monitoring sites for 2009.

Monitor Label	Monitor Description	Latitude	Longitude
OZ20-Active	Continuous	44º 03' 58.8"	-103º 28' 56.9"
OZ20	Passive	44º 03' 58.8"	-103º 28' 56.9"
OZ21-Tree	Passive	44º 03' 8.5"	-103º 28' 56.9"
OZ22-2M-DUP	Passive	44º 03' 8.7"	-103º 29' 28.7"
OZ22-2M	Passive	44º 03' 8.7"	-103º 29' 28.7"
OZ22-5M	Passive	44º 03' 8.7"	-103º 29' 28.7"
OZ22-8M	Passive	44º 03' 8.7"	-103º 29' 28.7"
OZ22-Blank	Passive	44º 03' 8.7"	-103º 29' 28.7"
OZ23-2M	Passive	44º 03' 3.9"	-103º 29' 21.1"
OZ23-5M	Passive	44º 03' 3.9"	-103º 29' 21.1"
OZ23-8M	Passive	44º 03' 3.9"	-103º 29' 21.1"

4.12 Task 12: Data analysis

Statistical relationships of foliage ion concentrations of sodium, magnesium and chloride were analyzed to assess relationships to distance from the road, orientation (up or down slope from road), and presence or absence of symptoms. Statistical relationships of foliage ion concentrations of sodium, magnesium and chloride were analyzed using the SAS[1] (Statistical Analysis System) TTEST Procedure and these were performed as two sample t-tests where TTEST computed the sample means for each of the two groups and tested the hypothesis that the population means differed by a given amount. The effects of various sources of variation (e.g., distance, symptoms, orientation) on the dependent variables (e.g., foliage ion concentration of chloride, magnesium and sodium) were analyzed. The TTEST computes the group comparison *t* statistic based on the assumption that the variances of the two groups are equal. It also computes an approximate *t* based on the assumption that the variances are not equal using the Satterthwaite's approximation to compute the degrees of freedom associated with the approximate *t*. The F statistic is computed to test for equality of the group variances. Differences were considered significant if $P < 0.05$.

Statistical relationships of extractable soil ion amounts of sodium, magnesium and chloride were analyzed to assess relationships to soil depth, distance from the road, orientation (up or down slope from road) and presence or absence of symptoms. Statistical relationships of soil amounts of extractable sodium, magnesium, and chloride were analyzed using the SAS GLM Procedure (PROC GLM), which uses the method of least squares to fit (see footnote) general linear models. The method involves the partition of variation (analysis of variance, ANOVA) in a dependent variable (e.g., chloride, magnesium and sodium) described as treatments. The locations for orientation (upslope vs. downslope), distance (3, 20, and 60 feet), and soil sample depth (0-6, 6-12, and 12-24 inches) were measured for both symptomatic and asymptomatic sites to provide a balanced statistical design. Mean between treatments and levels within treatments were considered significant if the P significance value (*P)* was < 0.05.

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[1] [1]The data analysis for this paper was generated using SAS software. Copyright, SAS Institute Inc. SAS and all other SAS Institute Inc. product or service names are registered trademarks or trademarks of SAS Institute Inc., Cary, NC, USA.

Dr. Gemechis Dijra, Associate Professor, Department of Mathematics and Statistics at SDSU, performed the statistical analysis.

4.13 Final report

This report constitutes the final report. It includes the literature review and the research teams' findings, conclusions, and recommendation.

4.14 Task 14: Executive presentation

The executive presentation to the SDDOT Research Review Board was held on November 27, 2017.

5 FINDINGS AND CONCLUSIONS

5.1 South Dakota Department of Transportation maintenance standards

Snow and ice removal for the safety of motorists is a primary concern for the SDDOT which had written standards outlining deicing practices. SDDOT Operating Performance Standards 1975 were in affect during the period of this study. Since the completion of this research the SDDOT has changed its deicing practices. They are using salt rather than a salt/sand blend to reduce the expense of transporting and spreading sand while also reducing dust generation.

During the period of this study, standards dictated that snow and ice be removed from road surfaces and shoulders using abrasives (sand) and a deicing salt (sodium chloride). A liquid deicing chemical (magnesium chloride) was occasionally used as a pre-treatment. The sand: salt blend was applied by a truck-mounted spreader and any pre-treatment was added as the blend left the spreader. Snow and ice removal operations were conducted from 5:00 am until 7:00 pm. unless additional work hours were authorized by the maintenance supervisor.

The order in which roads were deiced and how often they were deiced depended upon their priority levels, which were based upon the quantity of traffic on those roads. First priority roads were plowed once every two hours when time and labor permitted. Secondary priority roads were cleared once every four hours when time and manpower permitted. Tertiary priority was given to all remaining service roads, local intersections, and additional areas according to SDDOT Operating Performance Standards.

5.2 South Dakota Department of Transportation maintenance units

The SDDOT is divided into four Regions; Aberdeen, Mitchell, Pierre, and Rapid City. Each of these Regions is divided to three Areas. The Areas in the Rapid City Region are Belle Fourche, Custer, and Rapid City with the latter two responsible for highways within the Black Hills. Areas are further divided into two maintenance units. The Rapid City Area is divided into Maintenance Units 451 and 452. The Custer Area is divided into Maintenance Units 491 and 492.

The primary deicing salt used by the SDDOT during the study sampling time period (2006-2008) was sodium chloride blended with sand. The rate for application for this blend was approximately 100 to 300 pounds per lane mile. Along curves, on bridges or stretches of roads that were shaded for long periods of time, crews applied the salt/sand blend at rates up to about 800 pounds per lane-mile. Vehicles dispersing the blend were not to exceed 15 to 30 mph.

This blend was sometimes pre-wetted with a 30 percent liquid solution of magnesium chloride. The solution was sprayed on the sodium chloride and sand blend as it left the spreader and was applied at the rate of approximately six gallons of solution per lane mile.

5.2.1 Maintenance Unit 451 (Sturgis)

Maintenance Unit 451 was responsible for priority routes including US14A from Deadwood to Sturgis, US85 from Deadwood to the intersection of Interstate 90, and US385 from the intersection of US385 and SD44 to Deadwood. Non-priority routes for this unit consisted of US85 from Deadwood to the Wyoming border and US14A through Spearfish Canyon (Figure 5-1).

Sturgis used sodium chloride and sand as a deicing material during the sampling time period (2006-2008). Sturgis also pre-wetted this blend with a 30 percent solution of magnesium chloride, but only when roads were snow-covered.

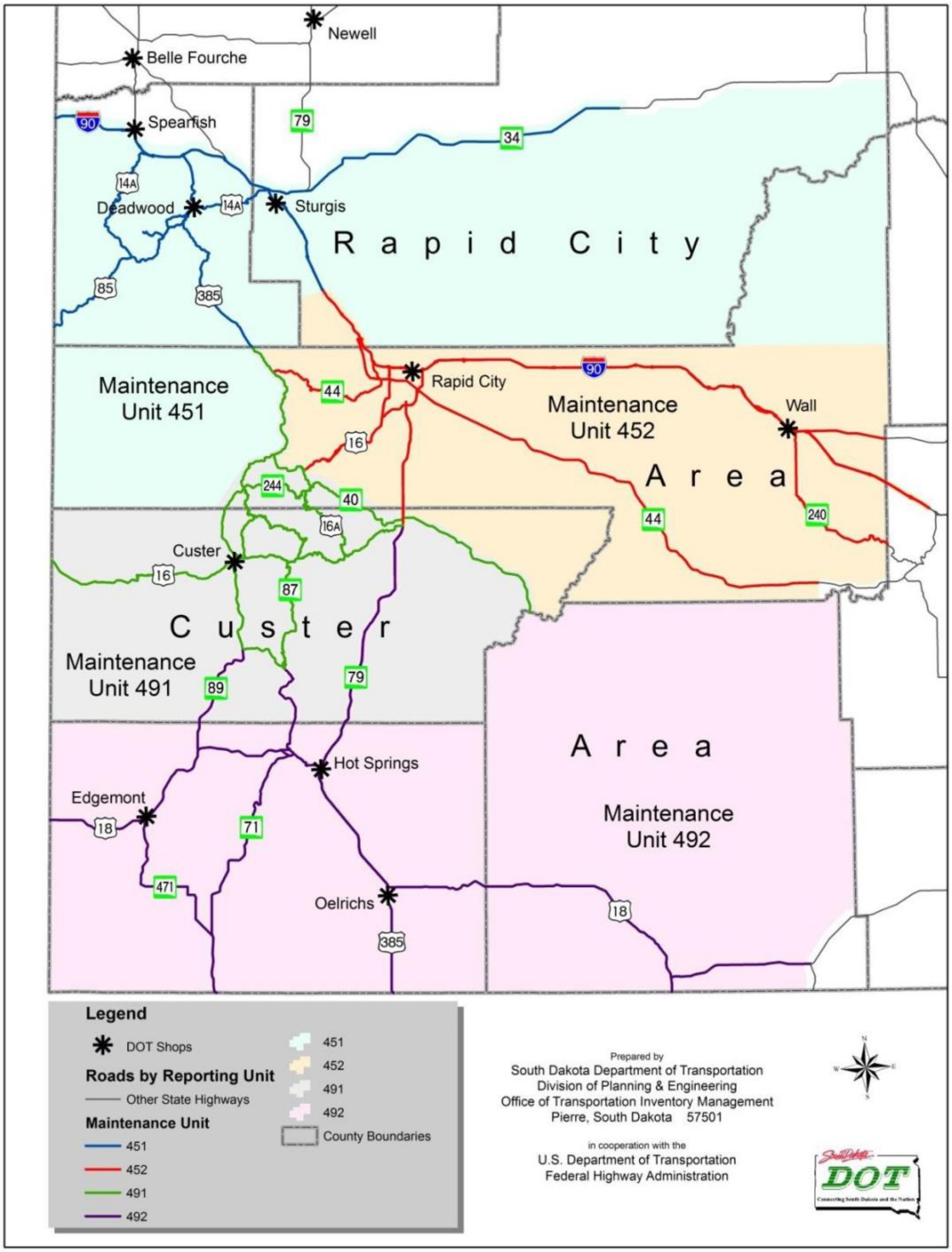

Figure 5-1. South Dakota Department of Transportation Zones of Responsibility.

5.2.2 Maintenance Unit 452 (Rapid City)

Maintenance Unit 452 was responsible for maintaining SD44, US16, and US385 from the intersection of US385nd US16 north to the intersection of US385 and SD44 (Figure 5-1). The unit employed a 16 percent sodium chloride and 84 percent sand (by weight) blend during the soil and foliage sampling time period of this study.

5.2.3 Maintenance Unit 491 (Custer)

Maintenance Unit 491 was responsible for maintaining US16 and US385 and US16 south of Custer to the town of Pringle and north of Custer to the southern boundary of the Rapid City zone of responsibility. Custer non-priority routes included SD244, SD87, SD89, SD40, and SD36 (Figure 5-1).

Maintenance Unit 491 used sodium chloride on some of its roadways including US385 and SD89 during the sampling period. They used small amounts of magnesium chloride as a pre-wetting liquid on US385 and none on SD89. US16A received limited sodium chloride deicing salt as did the junction of US16A and SD36 north to the Playhouse Road. The Playhouse Road north to US16A and intersections at Keystone received very little salt. US385 south to Wind Cave National Park had only sand applied by the SDDOT.

5.2.4 Maintenance Unit 492 (Hot Springs)

Maintenance Unit 492 was responsible for maintaining US16, US18, US385, and SD79 as priority routes. Non-priority routes included SD87, SD89, SD40, and SD36 (Figure 5-1).

While SDDOT able to provide total amounts of sodium chloride and magnesium chloride applied in the Black Hills during the study period, it was unable to provide documentation concerning application dates or the amounts of deicing salt applied along specific sections of highways. However, they could provide annual amounts used by maintenance unit (Table 5-1).

Table 5-1. SDDOT use of sodium chloride (NaCl) (pounds) and magnesium chloride ($MgCl_2$) (gallons) on Black Hills highways in fiscal years (FY) 2006-2009.

Unit	FY2006		FY2007		FY2008		FY2009	
	NaCl	$MgCl_2$	NaCl	$MgCl_2$	NaCl	$MgCl_2$	NaCl	$MgCl_2$
451	5,480,978	159,023	3,149,520	113,184	7,243,985	101,409	4,412,000	66,339
452	4,747,786	153,039	4,528,182	109,179	6,367,699	202,421	5,458,000	106,680
491	2,691,300	148,300	3,990,529	119,746	2,733,907	93,234	3,538,000	87,438
492	2,145,100	18,863	2,039,300	17,011	1,873,950	45,224	1,638,000	19,092
Total	15,065,164	479,225	13,707,531	359,120	18,219,541	442,288	15,046,000	279,549

The overall rates of deicing salts applied on highways in the Black Hills during the study period, about 100 to 300 pounds of sodium chloride per lane mile and magnesium chloride at six gallons per lane mile, were similar to or less than those reportedly made on other highway systems. Trahan and Peterson (2007) reported that sodium chloride was applied in a sand/salt blend at the rate of 500 pounds per lane mile and the liquid magnesium chloride solution applied at a rate between 40 and 80 gallons per lane mile in Colorado. Cunningham and others (2007) reported that sodium chloride was used in a sand/salt blend at a rate of about 250 pounds per lane mile in New York. In Massachusetts, the rate of sodium chloride applied was about 240 pounds per lane mile (Bryson and Barker, 2002).

5.3 Highway survey regarding the condition of roadside pines

The survey covered 346 miles of highways in the Black Hills of South Dakota on the 13 state highways within the responsibility of Maintenance Units 451, 452, 491, and 492. Approximately two-thirds of the 376 observation points along these roads had trees within 60 feet of the road centerline with ponderosa pine the only or dominant species on about 97 percent of these points (Table 5-2). The condition of the pines was evaluated by two characteristics, crown dieback and foliage color.

Table 5-2. South Dakota Black Hills Highway observation points.

Observation points forest composition	Total
Total points	376
Points with pines within 60 feet of the road centerline	238
Points with other tree species within 60 feet of the road centerline	7

5.3.1 Canopy dieback survey results

The percentage of canopy dieback was evaluated on pines at every observation point in which these trees occurred. Dieback can be attributed to either root or trunk injury that reduces water and nutrient transport to the foliage or direct injury to the foliage. Deicing salt exposure can cause the premature loss of needles in pines resulting in dieback of branches over time (Hofstra et al., 1979). Dieback is an indicator of the accumulation of past stresses and does not necessarily represent the current physiological condition of the tree (Schomaker et al., 2006: Wargo, 1978). Hence, dieback is a better indicator of past exposure to stressors rather than to a current stress event. The ponderosa pines on slightly more than 70 percent of these observation points exhibited less than five percent dieback during the 2007 survey. Slightly less than five percent of the 2007 points had pines exhibiting moderate (15 to 30 percent) dieback No observation points contained pines which exhibited more than 30 percent dieback (Table 5-3).

Table 5-3. Comparison of ponderosa pine dieback between the South Dakota Black Hills highway surveys in 2007 and 2011.

Crown dieback	2007	2011
No dieback, 0% dieback	47	5
Minimal dieback (< 5% dieback)	122	51
Light dieback (>5% to 15% dieback)	58	171
Moderate dieback (>15% but <30% dieback)	11	11
Severe dieback (>30% but < 50% dieback)	0	0
Extreme dieback (>50% dieback)	0	0

Ponderosa pines on slightly more than 23 percent of the observation points presented less than five percent dieback during the 2011 survey, a substantial decline from the 2007 survey. There was also an increase in the number of points that had trees presenting between five and 15 percent crown dieback. It would be unlikely to see any decrease in dieback in pine trees presenting more than five percent dieback over this short of a time period as the dieback is an accumulative process on conifers such as pines. Conifers, unlike deciduous trees, lack the capability to grow from adventitious buds. Deciduous trees form adventitious shoots near the juncture between the living and dead tissue on the branches that die back. These adventitious shoots can quickly grow and restore the canopy. Branches that die back on conifer do not generate adventitious shoots so branches that have died back will not produce new shoots. Shoots will only be produced from interior uninjured tips and these will eventually grow over the dead shoots and branches. Consequently, canopy dieback will remain visible for many years on pines even as the tree recovers. Dieback is a better indicator of the accumulation of past stresses rather than of current conditions. The dieback observed in 2011 was a reflection of the accumulation of stress during previous decade, rather than the severity of stress in 2011.

5.3.2 Canopy foliage color survey results

Foliage color is a better measure of the current condition of a canopy (Weaver and Stipes, 1990). Ponderosa pine's foliage color is generally a dark gray green (Harlow and Harrar, 1969), which is the source of the name for the region, the Black Hills. The dominant foliage color (i.e., the color of more than 50 percent of the foliage) of trees on 19 percent of the points was a normal dark gray-green in the 2007 survey, but this increased to 63 percent of the points by the 2011(Table 5-4). The change in color from a light green or yellow-green to a dark gray-green indicated a recovery from stress.

Table 5-4. Comparison of crown foliage color between the South Dakota Black Hills state highway surveys in 2007 and 2011.

Crown foliage color	2007	2011
Dark gray-green to green	42	151
Green to yellow-green	126	80
Yellow-green	59	7
Yellow	11	0
Yellow brown	0	0
Ash-gray	0	0

5.4 Investigation of deicing salts in soils and pine foliage

Four sites—and within each of these sites two locations, asymptomatic and symptomatic—were selected for collecting pine foliage and soil samples. The symptomatic locations (i.e., pines within 20 to 30 feet from the pavement edge with canopies exhibiting symptoms associated with deicing salt injury) and asymptomatic locations (i.e., pines within 20 to 30 feet from the pavement edge with normal appearing canopies) at each of the four sites (Box Elder, Pactola, Sheridan, and Sylvan) are identified in the following sections. The map for each of the sites identifies locations as AD, AU, SD, SU to indicate Asymptomatic Downslope from road, Asymptomatic Upslope from road, Symptomatic Downslope from road, and Symptomatic Upslope from road respectively (Table 5-5).

Table 5-5. Site characteristics for the deicing research.

Site #	Site name	Symptoms	Elevation (ft)	Up Slope	Down Slope
1	Box Elder	Symptomatic	5410	10°	30°
		Asymptomatic	5400	15°	30°
2	Pactola	Symptomatic	4800	15°	30°
		Asymptomatic	4800	15°	30°
3	Sheridan	Symptomatic	5130	15°	30°
		Asymptomatic	5070	15°	40°
4	Sylvan	Symptomatic	6265	20°	25°
		Asymptomatic	6275	15°	15°

5.4.1 Site locations and descriptions

The Box Elder paired (Figure 5-2) asymptomatic (Figure 5-3) and symptomatic (Figure 5-4) locations (site #1) were situated about 0.6 miles north of Boxelder Creek on US385. This section of US385 was maintained by Maintenance Unit 451 (Sturgis). The average daily traffic (ADT) for this section of road was 1385 vehicles per day (South Dakota Department of Transportation, 2007).

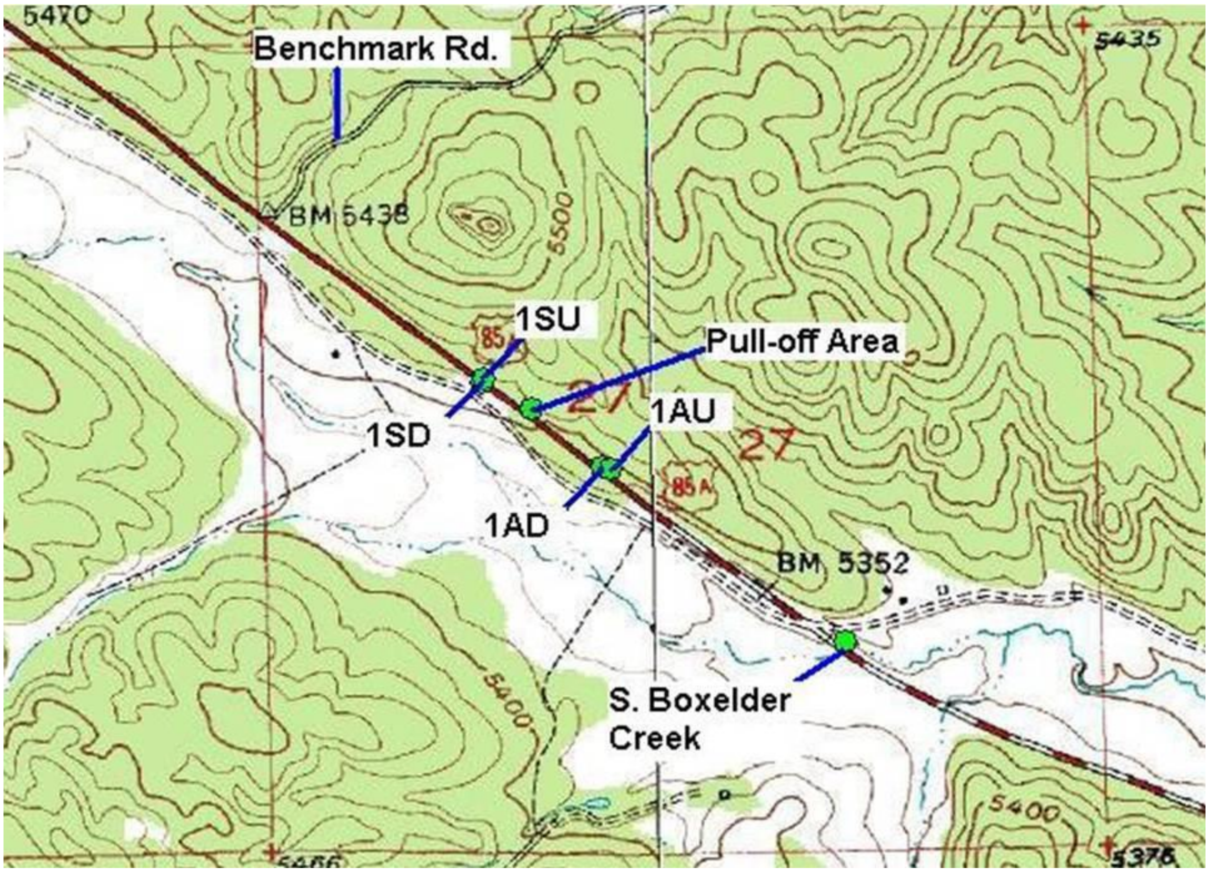

Figure 5-2. Box Elder (Site #1) asymptomatic and symptomatic sampling locations.

Figure 5-3. Asymptomatic location, Box Elder site.

Figure 5-4. Symptomatic location, Box Elder site.

The Pactola paired (Figure 5-5) asymptomatic (Figure 5-6) and symptomatic (Figure 5-7) locations (site #2) were located 1.2 miles north of Pactola Reservoir on US385. The highway at this site was maintained by Maintenance Unit 452 (Rapid City). The ADT for this section of road was about 1442 vehicles per day (South Dakota Department of Transportation, 2007).

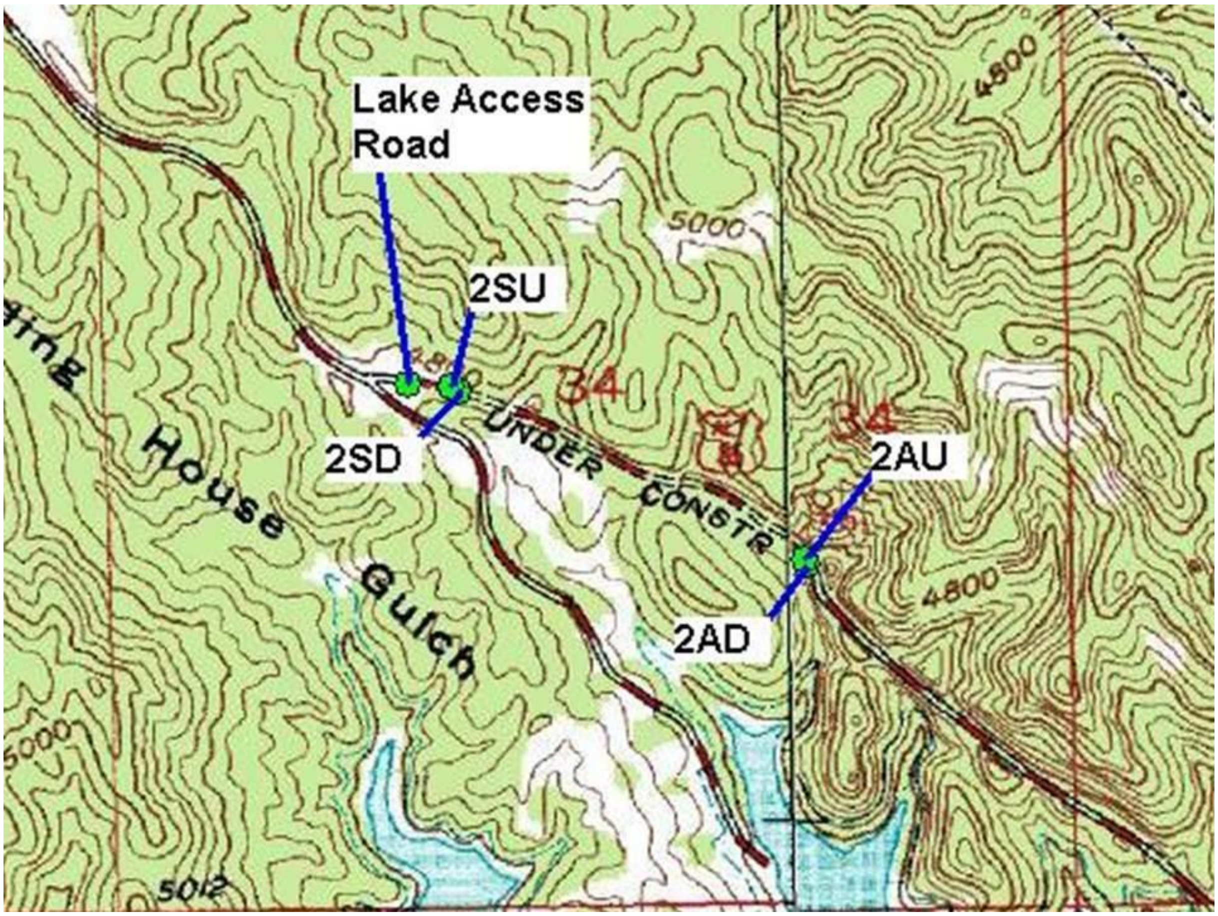

Figure 5-5. Pactola (Site #2) asymptomatic and symptomatic sampling locations.

Figure 5-6. Asymptomatic location, Pactola site.

Figure 5-7. Symptomatic location, Pactola site.

The Sheridan paired (Figure 5-8) asymptomatic (Figure 5-9) and symptomatic (Figure 5-10) locations (site #3) were located about 1.2 miles north of Sheridan Lake and 8 miles south of Pactola Reservoir on US385. The section of the highway was maintained by Maintenance Unit 452 (Rapid City). The ADT for this segment of US385 was 1596 vehicles per day (South Dakota Department of Transportation, 2007).

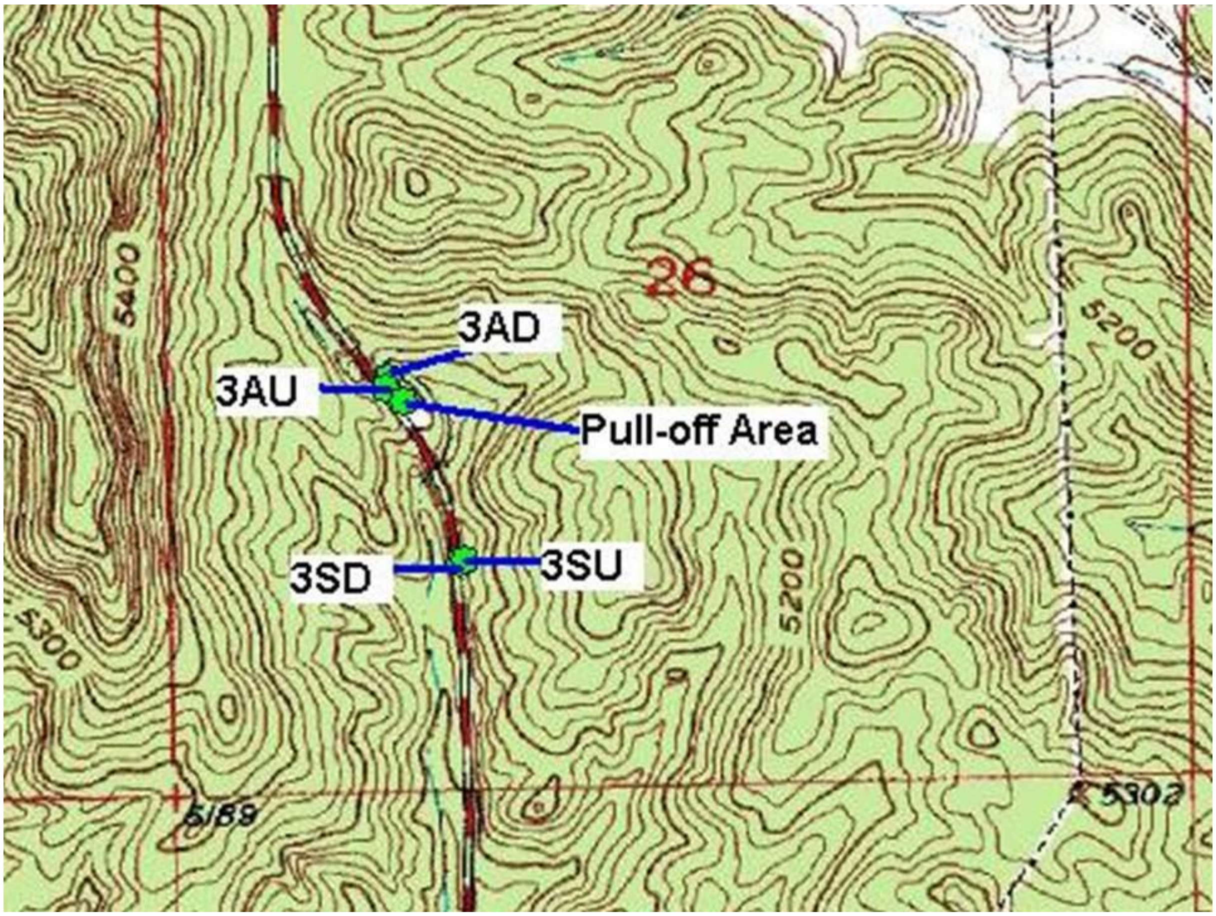

Figure 5-8. Sheridan (Site #3) asymptomatic and symptomatic sampling locations.

Figure 5-9. Asymptomatic location, Sheridan site.

Figure 5-10. Symptomatic location, Sheridan site.

The Sylvan paired (Figure 5-11) asymptomatic (Figure 5-12) and symptomatic (Figure 5-13) locations (site #4) were located on SD87 about 0.6 miles west of the intersection with SD89. The section of the highway was maintained by Maintenance Unit 491 (Custer). The ADT for SD87 was 480 vehicles per day (South Dakota Department of Transportation, 2007).

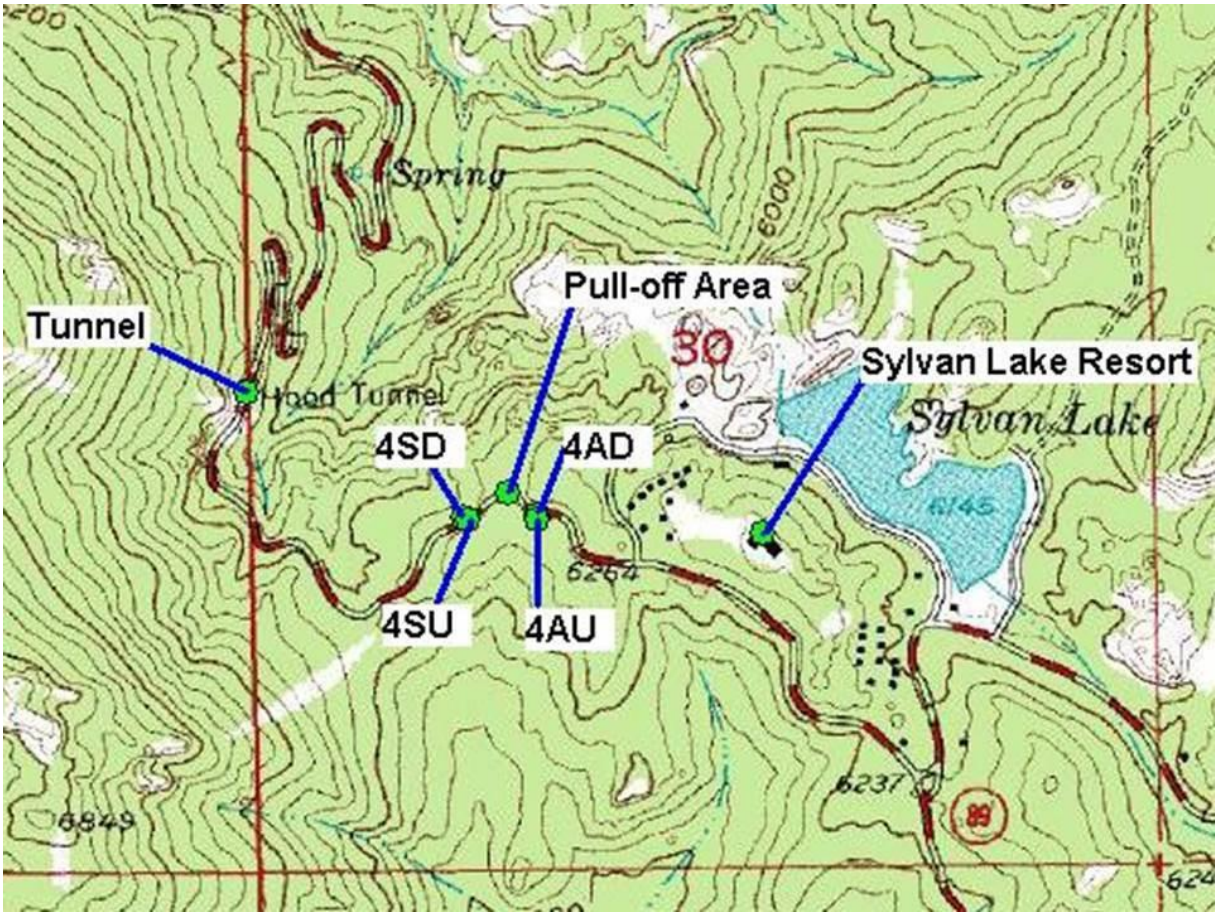

Figure 5-11. Sylvan (Site #4) asymptomatic and symptomatic sampling locations.

Figure 5-12. Asymptomatic location, Sylvan site.

Figure 5-13. Symptomatic location, Sylvan site.

5.4.2 Description of the vegetation on the study sites

The Black Hills are dominated by ponderosa pine forests and all the study sites included mature pines (Table 5-6). The sites were also within the ponderosa pine/snowberry (*Pinus ponderosa* /*Symphoricarpos occidentalis*) habitat type, the most common habitat type in the Black Hills (Shepperd and Battaglia, 2002). The overstory for this habitat type is dominated by pine, but may also include aspen (*Populus tremuloides*) and paper birch (*Betula papyrifera*), and the understory contains mostly open grown shrubs. The herbaceous layer is very diverse and is composed of ricegrass (*Oryzopsis*), oatgrass (*Danthonia*), and sedge (*Carex*).

Table 5-6. Ponderosa pine characteristics for the study sites.

Site #	Site name	Locations	Mean Tree Height (ft)	Mean DBH (in)
1	Box Elder	Symptomatic	36	15
		Asymptomatic	32	18
2	Pactola	Symptomatic	26	9
		Asymptomatic	37	11
3	Sheridan	Symptomatic	34	15
		Asymptomatic	26	12
4	Sylvan	Symptomatic	25	7
		Asymptomatic	32	16

5.4.3 Description of the soils on the study sites

The soil order that dominates the Black Hill except for prairie inclusions is Alfisol (Radeke and Westin, 1963). The soil series within this order that occurred on the sampling sites were Buska and Pactola, along with rock outcrops at one of the sampling sites (Table 5-7). All are common soils within the Central Crystalline Core of the Black Hills. The soils are channery, consisting of at least 15 percent (by volume) of flat fragments of sandstone, shale, slate, limestone, or schist which may be up to six inches along the longest axis. The Buska and Pactola soils are both deep and well-drained and occur on slopes from 6 to 60 percent. The USDA classification for Pactola series is Loamy-skeletal, mixed superactive frigid Glossic Hapludalfs and for the Buska series a loamy-skeletal, mixed micaceous, frigid Glossic Hapludalfs. The USDA classification for Rocky Outcrop is loamy-skeletal, mixed superactive Lithic Udorthents (Soil Survey staff, 2014).

Table 5-7. Site soil classification and texture by depth.

	Site	#1: Box Elder	#2: Pactola	#3: Sheridan	#4: Sylvan
	Soil Series	Pactola	Rock Outcrop	Pactola	Buska
Soil Texture	1 to 11 inches (2.5-28 cm)	Channery Loam	Channery Loam	Channery Loam	Loam
	11 to 18 inches (28-46 cm)	Channery Clay Loam	Very Channery Loam	Channery Clay Loam	Channery Loam
	18 to 48 inches (46-117cm)	Channery Clay Loam	Extremely Channery Clay Loam	Channery Clay Loam	Very Channery Loam

5.4.4 Foliage nutrient content of the pines from the four study sites

Foliage sampling took place during four periods, late summer (August/September) 2006 and 2007 and late spring (May/June) 2007 and 2008. At each site, foliage samples were collected from a ponderosa pine about 20 feet from the pavement edge, generally the closest distance mature trees occurred along the highways, and another ponderosa pine approximately 60 feet from the road centerline. Sampling occurred on both sides of the road so two trees were sampled at approximately 20 feet and two at approximately 60 feet at each of the eight sites, four symptomatic locations and four asymptomatic locations.

The four symptomatic sites had pines at about 20 feet from the pavement presenting canopy symptoms—discolored foliage and branch dieback—commonly associated with exposure to deicing salts. These pines were usually among the closest mature trees to the road. The space closer to the road was generally occupied by ponderosa pine saplings, trees less than 4 inches in diameter at 4.5 feet above the ground, or seedlings, trees less than three feet tall, and herbaceous plants. The mature pine trees at 60 feet from the road centerline did not exhibit symptoms of exposure to deicing salts regardless of whether they occurred on a symptomatic or asymptomatic location.

5.4.4.1 Total foliage Na content

Sodium is a normal, though minor, component of pine foliage. Blinn and Bucker (1989) reported that the typical concentration of this nutrient in pine foliage ranged from 0.01 to 0.05 (percent dry weight) depending upon the species. Spotts and others (1972) found ponderosa pine foliage contains less than 0.01 sodium percent dry foliage weight. Sodium is not considered an essential nutrient for tree growth (Gauch 1972) and the literature on the effect of sodium in woody vegetation is directed to its potential toxicity rather than possible benefit. Sodium has been reported to cause visible injury to conifer foliage at concentrations above 0.2 to 0.5 percent dry weight (Hofstra and Hall, 1971; Hofstra et al., 1976).

Foliar sodium concentrations in the ponderosa pines at the four sites during the four sampling time periods ranged from a low of 0.001 (as a percent of dry needle weight) to a high of 0.31. The only trees with sodium foliage concentrations greater than 0.2 percent dry weight for any of the sampling time periods were three of the four pines at 20 feet from the pavement edge on upslope symptomatic location. There was a statistically significant difference in the mean sodium foliage concentration between pines on asymptomatic and symptomatic location 20 feet from the pavement edge (Table 5-8).

Table 5-8. Sample number (N), mean, standard error of the means (SE), and P significance value (P) for comparisons of foliage sodium (Na) concentrations (percent dry weight) in ponderosa pine at 20 feet from the pavement edge on asymptomatic and symptomatic locations (TTEST in Appendix A-1).

Symptoms	N	Mean	SE	P
Asymptomatic	32	0.01	0.00	0.0019
Symptomatic	32	0.07	0.02	

The mean concentration of sodium in pine foliage 20 feet from the pavement edge on the symptomatic location, 0.07 percent dry weight, was below the threshold, 0.2 percent dry weight, where foliage injury typically is seen on pine. The trees on symptomatic locations at 20 feet had a significant difference in mean foliage sodium concentrations compared with the trees at 60 feet from the center line of the road (Table 5-9). This was also true for the asymptomatic locations where there was also a significant difference between the trees at 20 feet and 60 feet in mean foliage concentrations of sodium (Table 5-10). The concentrations of sodium found in the foliage of trees at 20 feet from the pavement were higher than those at 60 feet from the road centerline regardless of whether the trees were on asymptomatic or symptomatic locations. These results were consistent with the findings of others that have investigated the effects of sodium chloride as a deicing salt noting that the foliage concentration of sodium decreased with distances from the road (McBean and Al-Nassri, 1987; Viskari and Karenlampi, 2000; Blomqvist and Johansson, 1999; Foreman and Alexander, 1998).

Table 5-9. Sample number (N), mean, standard error of the means (SE), and P significance value (P) for comparisons of foliage sodium (Na) concentrations (percent dry weight) for ponderosa pines at 20 feet from the pavement edge and 60 feet from the road centerline on symptomatic locations (TTEST Procedure in Appendix A-2).

Distance	N	Mean	SE	P
20 feet	32	0.07	0.02	0.0020
60 feet	32	0.01	0.01	

Table 5-10. Sample number (N), mean, standard error of the means (SE), and P significance value (P) for comparisons of foliage sodium (Na) concentrations (percent dry weight) for ponderosa pines at 20 feet from the pavement edge and 60 feet from the road centerline on asymptomatic locations (TTEST Procedure in Appendix A-3).

Distance	N	Mean	SE	P
20 feet	32	0.01	0.00	0.0266
60 feet	32	0.00	0.00	

Previous researchers found elevated foliar sodium as far as 400 feet from the road (Hofstra and Hall, 1971). Blomqvist and Johansson (1999) noted elevated foliar sodium at distances of 1,300 feet from the highway. However, Kelsey and Hootman (1992) noted only slightly higher concentrations than normal at this distance. Trahan and Peterson (2007) found foliage sodium (percent dry weight) of 0.15 percent for ponderosa pines next to the highway and 0.06 percent for trees 150 to 300 feet from the road. Bryson and Barker (2002) in a Massachusetts study of sodium accumulation in roadside pines found needles contained 0.34 sodium (percent dry weight) at 10 feet from the road and this concentration decreased by almost half in pine foliage by 20 feet from road. In this study the foliage sodium concentrations in pines located at 60 feet from the road centerline was less than 0.01 (percent dry weight), a concentration that is normal for ponderosa pines and much less than what was detected in other deicing studies at this distance. There was no significant difference between autumn and spring foliage concentrations in pines at 20 feet from the pavement edge at either asymptomatic (Table 5-11) or symptomatic (Table 5-12) locations. However, the mean foliage sodium concentration (percent dry weight) was highest in the spring sampling (2007 and 2008) and the lowest in the autumn sampling (2006 and 2007).

Table 5-11. Sample number (N), mean, standard error of the means (SE), and P significance value (P) for comparisons of foliage sodium (Na) concentrations (percent dry weight) for ponderosa pines on asymptomatic locations at 20 feet from the pavement edge by sampling season (TTEST in Appendix A-4).

Season	N	Mean	SE	P
Autumn	16	0.01	0.00	0.2030
Spring	16	0.01	0.00	

Table 5-12. Sample number (N), mean, standard error of the means (SE), and P significance value (P) for comparisons of foliage sodium (Na) concentrations (percent dry weight) for ponderosa pines on symptomatic locations at 20 feet from the pavement edge by sampling season (TTEST in Appendix A-5).

Season	N	Mean	SE	P
Autumn	16	0.05	0.02	0.2340
Spring	16	0.09	0.03	

5.4.4.2 Total foliage Mg content

Magnesium is an essential nutrient for tree growth, being a constituent of the chlorophyll molecule important in photosynthesis. Magnesium is generally discussed in the literature regarding correcting deficiencies in trees rather than as a toxin as abundant concentrations of this nutrient in the tree are not consisted harmful (Harris et al., 2004). The typical magnesium concentration in pine foliage is between 0.09 and 0.12 percent dry weight (Palomaki, 1995), though Allen (1987) reported even lower magnesium concentrations, 0.05 percent dry weight, in healthy ponderosa pines. Garreton-Johnston and others (2005) reported a foliage magnesium concentration range of 0.07 to 0.12 percent dry weight for mature ponderosa pines. Spotts and others (1972) noted healthy ponderosa pine seedlings had a foliage magnesium concentration of 0.17 percent dry weight.

Foliage magnesium concentration in the plots ranged from a low of 0.08 (percent dry weight) to a high of 0.21. The presence of slightly higher concentrations than occur normally suggests that these trees may have accumulated magnesium from it being applied as a pre-wetting liquid during road deicing operations. However, the foliage concentrations were still just slightly higher than normal and very low compared to those reported for other deicing salt studies. Trahan and Peterson (2007) noted foliage concentrations of 0.51 percent dry weight in the roadside ponderosa pines in the Denver area that were presenting symptoms of deicing salt stress from magnesium chloride applications.

The highest foliage magnesium concentrations were in trees 20 feet from the pavement edge and at symptomatic locations. However, there was no significant difference in the mean foliage concentrations of magnesium in trees at 20 feet between asymptomatic or symptomatic locations (Table 5-13).

Table 5-13. Sample number (N), mean, standard error of the means (SE), and P significance value (P) for comparisons of foliage magnesium (Mg) concentrations (percent dry weight) for ponderosa pines at 20 feet from pavement edge on asymptomatic and symptomatic locations (TTEST in Appendix A6).

Symptom	N	Mean	SE	P
Asymptomatic	32	0.12	0.01	0.5251
Symptomatic	32	0.13	0.00	

There was also no significant difference in the mean magnesium concentrations in the foliage between trees on symptomatic locations at 20 feet or 60 feet (Table 5-14) or between the trees at asymptomatic locations at 20 and 60 feet (Table 5-15). The mean foliage concentration for magnesium on all sites is only slightly above the upper end of the normal range reported by Garreton-Johnston and others (2005).

The use of magnesium chloride as a pre-wetting solution by the SDDOT during the time period of this study appears to have been too low to result in a significant increase of this nutrient in the pine foliage.

Table 5-14. Sample number (N), mean, standard error of the means (SE), and P significance value (P) for comparisons of foliage magnesium (Mg) concentrations (percent dry weight) for ponderosa pines at 20 feet from the pavement edge and 60 feet from the road centerline on symptomatic locations (TTEST in Appendix A-7).

Distance	N	Mean	SE	P
20 feet	32	0.13	0.01	0.8825
60 feet	32	0.13	0.00	

Table 5-15. Sample number (N), mean, standard error of the means (SE), and P significance value (P) for comparisons of foliage magnesium (Mg) concentrations (percent dry weight) for ponderosa pines at 20 feet from the pavement edge and 60 feet from the road centerline on asymptomatic locations (TTEST in Appendix A-8).

Distance	N	Mean	SE	P
20 feet	32	0.12	0.01	0.6326
60 feet	32	0.12	0.01	

There was no significant difference between autumn and spring mean magnesium foliage concentrations (percent dry weight) on either the pines at 20 feet on asymptomatic (Table 5-16) or symptomatic (Table 5-17) locations. There were only slightly higher mean foliage concentrations of magnesium in the spring samplings (2007 and 2008) than the autumn samplings (2006 and 2007).

Table 5-16. Sample number (N), mean, standard error of the means (SE), and P significance value (P) for comparisons of foliage magnesium (Mg) concentrations (percent dry weight) for ponderosa pines on asymptomatic locations at 20 feet from the pavement edge by sampling season (TTEST in Appendix A-9).

Season	N	Mean	SE	P
Autumn	16	0.13	0.01	0.3492
Spring	16	0.12	0.01	

Table 5-17. Sample number (N), mean, standard error of the means (SE), and P significance value (P) for comparisons of foliage magnesium (Mg) concentrations (percent dry weight) for ponderosa pines on symptomatic locations at 20 feet from the pavement edge by sampling season (TTEST in Appendix A-10).

Season	N	Mean	SE	P
Autumn	16	0.13	0.01	0.5326
Spring	16	0.13	0.01	

5.4.4.3 Total foliage Cl content

Chlorine is an essential, though minor, nutrient for trees and is available to plants as the anion chloride (Cl^-) (White and Broadley, 2001). Chloride is necessary for photosynthesis and also facilitates water movement across cellular membranes. The typical concentration of chloride in pines is about 0.02 percent dry weight (Blinn and Becker, 1989). The concentration of chloride in healthy ponderosa pine foliage is approximately 0.02 (Hagle, 2002) to 0.04 percent dry weight (Spotts et al., 1972).

Chloride, while essential for plant function, can become toxic if the concentration increases beyond the small amount that is required. This may occur with deicing salt applications. Chloride is the deicing salt ion most responsible for plant injury and the foliage concentration of chloride is a better indicator of deicing injury than sodium (Scharpf and Srago, 1974). Severe foliage injury, discoloration, and dieback occurring in at least 75 percent of canopy has been observed in ponderosa pines with 0.5 percent chloride content (dry weight) in the foliage (Hagle, 2002). Trahan and Peterson (2007) observed foliage chloride concentrations in roadside ponderosa pines showing severe symptoms of deicing salt injury of 1.40 percent dry weight. Pines within the city limits of Rapid City exhibiting symptoms associated with deicing salts have been found with foliage chloride concentrations between 0.47 and 0.63 percent dry weight (Ball, 2005). These trees suffered extensive dieback and most died within a few years after beginning to exhibit symptoms.

Foliage chloride concentrations in the ponderosa pines at the four paired sites and over the four sampling times ranged from a low of 0.02 to a high of 1.67 percent dry weight. At each of the symptomatic locations, the ponderosa pines at approximately 20 feet from the pavement edge and the one on the upslope side from the road had chloride foliage concentration of at least 0.40 percent dry weight during at least one of the sampling times.

There was a significant difference in mean foliage chloride concentrations between asymptomatic and symptomatic locations for trees at 20 feet from the pavement edge (Table 5-18).

Table 5-18. Sample number (N), mean, standard error of the means (SE), and P significance value (P) for comparisons of foliage chloride (Cl) concentrations (percent dry weight) at 20 feet from the pavement edge for asymptomatic and symptomatic locations (TTEST in Appendix A-11).

Symptoms	N	Mean	SE	P
Asymptomatic	32	0.09	0.01	0.0020
Symptomatic	32	0.32	0.07	

There was also a significant difference in mean foliage chloride concentrations between trees at 20 and 60 feet for symptomatic (Table 5-19) and asymptomatic (Table 5-20) locations. Foliar chloride concentrations declined markedly between the trees at 20 feet from those at 60 feet.

Table 5-19. Sample number (N), mean, standard error of the means (SE), and P significance value (P) for comparisons of foliage chloride (Cl) concentrations (percent dry weight) at 20 feet from the pavement edge and 60 feet from the road centerline for ponderosa pines on symptomatic locations (TTEST in Appendix A-12).

Distance	N	Mean	SE	P
20 feet	32	0.32	0.07	0.0007
60 feet	32	0.06	0.01	

Table 5-20. Sample number (N), mean, standard error of the means (SE), and P significance value (P) for comparisons of foliage chloride (Cl) concentrations (percent dry weight) for ponderosa pines at 20 feet from the pavement edge and 60 feet from the road centerline on asymptomatic locations (TTEST in Appendix A-13).

Distance	N	Mean	SE	P
20 feet	32	0.09	0.01	0.0002
60 feet	32	0.06	0.00	

As observed with sodium, the foliage chloride concentrations observed in pines at 20 feet from the road edge on symptomatic sites were generally high enough to account for the foliage discoloration and dieback symptoms expressed by these pine trees.

There was also a significant difference in mean foliage chloride concentration with respect to orientation for trees on symptomatic sites at 20 feet from the road edge (Table 5-21). The trees on the upslope side of the road had significantly higher mean foliage concentrations of chloride than the trees on the downslope side of the road (Figure 5-14).

Table 5-21. Sample number (N), mean, standard error of the means (SE), and P significance value (P) for comparisons of foliage chloride (Cl) concentrations (percent dry weight) for ponderosa pines at 20 feet from the pavement edge on symptomatic locations by orientation (TTEST in Appendix A-14).

Orientation	N	Mean	SE	P
Downslope	16	0.14	0.03	0.0127
Upslope	16	0.49	0.13	

The orientation, upslope versus downslope, in itself may have little relationship to the foliage concentration of chloride. By chance, the upslope side of the road was also the east side of the road for three of the symptomatic locations and the remaining upslope location was on the south side of the road. The prevailing winds in the Black Hills during the winter and spring are from the west to northwest (South Dakota Climatology Lab, 2014) and this wind direction may explain the higher concentration of salts in the foliage. Hofstra and Hall (1971) observed greater injury and higher salt concentration in pines on the south and east side of the road in an area where the prevailing winter winds were also from the northwest. These airborne salts may originate not only from droplets containing salts carried from the west road surface, but also from dried salts carried on the wind as dust particles. Williams and others (2000) determined that the dominant vector for deicing salt deposition on foliage was deposition of dried salt on the roadway emitted as an aerosol and carried to the canopies. This was also observed by Blomqvist and Johansson (1999) who noted that traffic speed was a factor in the distance in which the salt aerosol was carried and the amount of the aerosol was reduce by one-third when traffic speeds was lowered from 55 mph to 40 mph.

There was no significant difference between autumn and spring foliage concentrations of foliage chloride (Cl^-) concentration (percent dry weight) for either asymptomatic (Table 5-22) or symptomatic (Table 5-23) sites. There were only slightly higher mean foliage concentrations of chloride found in the spring samplings (2007 and 2008) than the autumn samplings (2006 and 2007).

Table 5-22. Sample number (N), mean, standard error of the means (SE), and P significance value (P) for comparisons of foliage chloride (Cl) concentrations (percent dry weight) for ponderosa pines on asymptomatic locations at 20 feet from the pavement edge by sampling season (TTEST in Appendix A-15).

Season	N	Mean	SE	P
Autumn	16	0.09	0.01	0.7576
Spring	16	0.089	0.01	

Table 5-23. Sample number (N), mean, standard error of the means (SE), and P significance value (P) for comparisons of foliage chloride (Cl) concentrations (percent dry weight) for ponderosa pines on symptomatic locations at 20 feet from the pavement edge by sampling season (TTEST in Appendix A-16).

Season	N	Mean	SE	P
Autumn	16	0.28	0.08	0.5953
Spring	16	0.36	0.11	

5.4.4.4 Summary of foliage nutrient contents

The highest mean foliage concentrations of sodium and chloride were found in the spring sampling (2007 and 2008) and the lowest in the autumn sampling (2006 and 2007) for symptomatic pines at 20 feet from the pavement edge, though there was not a statistically significant difference between the mean foliage concentration between seasons for any of the ions. However, the slightly higher concentration in spring versus autumn foliage sampling is consistent with the findings of Lumis and others (1976), as they also noted for aerial spray of deicing salts the greatest concentration of salts in the foliage occurred at the end of the winter with concentrations declining throughout the summer.

There is little accumulation of salts in the foliage from year to year in foliage unless soil concentration of these ions is very high (Hall et al., 1972). The decline often seen from spring to autumn is due to the salt being leached from the foliage by rains (Hofstra et al., 1979). Salt absorption into the needles does not occur until the air temperatures exceed 36ºF and uptake increases in the spring as the temperatures reach 60ºF (Hofstra et al., 1979). Temperature fluctuations (freeze/thaws) also increase salt accumulation in trees (Lumis et al., 1976). Temperatures above freezing, as well as temperature fluctuations, are a common event in the Black Hills during the winter, so some uptake may occur throughout this time though the peak of absorption most likely occurs during the warm days in April. If high liquid precipitation occurs during this time of year or later into the spring, much of the salt may be washed from the needles before being absorbed (Viskari and Karenlampi, 2000).

The foliage concentration of sodium exceeded the normal levels only in the needles from trees at 20 feet from the road's edge on the symptomatic sites, and only on the upslope (Figure 5-14). These trees were also the ones most like exposed to drift since they were on the east side of the road. The foliage concentrations of chloride were above the normal range at all sites. However, the concentrations were slightly elevated in the foliage from trees on the asymptomatic sites (Figure 5-15) and the upslope trees at 60 feet on the symptomatic sites (Figure 5-14). The trees on the upslope on the symptomatic sites at 20 feet had the highest concentrations. These were also trees along with east side of the highways and the winds during late winter and early spring are predominantly out of the northeast.

The concentrations of the ions common in deicing salts, sodium and chloride, and the pattern in these concentrations with respect to asymptomatic versus symptomatic trees, season, distance from the road and orientation from the road all point to an aerial spray rather than runoff from the road as being the dominant vector for transporting deicing salts to the trees. The most likely source is road deicing salts that have dried on the pavement before being carried into the air by passing traffic during late winter and spring.

5.4.5 Soil extractable nutrient amounts of the four study sites

Soil sampling took place at the four sites during August/September 2006 and 2007 and May/June 2007 and 2008. At each site, soil samples were collected at three feet and 20 feet from the edge of the pavement and 60 feet from the road centerline. Sampling occurred on both sides of the road at each site. At each soil sampling location, soil samples were collected from three different depths: 0-6, 6-12, and 12-24 inches from the surface.

Ponderosa pine roots may extend as deep as four to five feet depending upon the soil texture with the shallower root systems developing in clay or clay loam soils (Berndt and Gibbon, 1958). The majority of the roots for ponderosa pine on clay loam are concentrated in the upper two feet (Oliver and Ryker, 1990). The non-woody root system of trees responsible for the absorption of water and nutrients generally occurs within the upper foot of the soil (Perry, 1982). The soils on the sites were channery loams (Table 5-7), either clay or silt loam, that would facilitate extensive non-woody root development in the upper foot of the soil and most of the woody roots in the upper two feet. Soil sampling was conducted within this depth.

5.4.5.1 Soil extractable Na^+ amounts

Sodium occurs naturally in the Black Hills and deposits of sodium bentonite are mined in the region (Knechtel and Patterson, 1962). Sodium, as well as magnesium, typically occurs at higher concentration in Alfisols, the soil order found in the Black Hills, than other soil orders. Extractable sodium amounts in the upper three inches of the soils in the Black Hills are approximately 0.05 meq/100 g, though this amount can be as high as near 0.1 meq/100 g (Kennedy et al. 1995). The amount increases with depth and may double between one and 24 inches in Alfisols (Jobbagy and Jackson 2001).

Sodium as a deicing agent can be carried from the road to the adjacent soil by runoff from the road surface, road splash, or aerial spray. Soil sodium amounts between 0.29 and 1.30 meq/100 g may result in injury to at least 25 percent of the roadside woody plants (Cani et al., 2001). Hootman and others (1994) determined the threshold for woody plant injury at 1.09 meq/100 g of soil sodium. Ponderosa pine seedlings may be killed by soil sodium amounts as low as 0.61 meq/100 g (Bedunah and Trilca 1977).

Extractable soil sodium amounts obtain from soil sampling during this study ranged from a low of 0.03 meq/100 g to a high of 4.20 meq/100 g. There was a significant difference in soil sodium with distance from the road with the highest amounts occurring three feet from the road edge. At 60 feet from the road centerline the mean sodium amount between one and 24 inches was 0.15 meq/100 g (Table 5-24).

Table 5-24. Sample number (N), mean, and standard error of the means (SE) for comparisons of amount (meq/100 g) of extractable sodium (Na^+) for 0-24 inches at 3 and 20 feet from the pavement edge and 60 feet from the road centerline (GLM in Appendix A-17).

Distance	N	Mean	SE
3 feet	185	0.82	0.04
20 feet	183	0.42	0.02
60 feet	185	0.15	0.01

Trahan and Peterson (2007) found soil sodium amounts between 0.54 and 1.47 meq/100 g in the upper foot of the soil near the road and 0.38 and 0.51 meq/100 g at 150 to 300 feet away. Barker (2000) noted elevated sodium amounts, 0.67 meq/100 g, at distances up to 20 feet from the road, but the amounts declined to 0.11 meq/100 g by a distance of 40 feet.

There was a significant difference in the mean extractable soil sodium amounts between asymptomatic and symptomatic locations at 20 feet from the pavement edge (Table 5-25). However, the mean soil sodium amount on the symptomatic sites at 20 feet was still below the threshold for injury to ponderosa pines. There was no significant difference (P=0.2527) in mean extractable soil sodium amounts between asymptomatic and symptomatic locations at 60 feet from the road centerline (Appendix Table A-20). There was a significant difference (P=0.0176) among soil depths for the mean extractable sodium amounts at three feet from the pavement with the amount increased with depth (Appendix Table A-19). This is consistent with the findings of Cunningham and others (2008), who also observed that soil sodium amounts increased with depth. There were no significant differences in mean extractable soil sodium amounts among soil depths at 20 feet or 60 feet (Table 5-26).

Table 5-25. Sample number (N), mean, standard error of the means (SE), and P significance value (P) for comparisons of amount (meq/100 g) of extractable soil sodium (Na^+) between locations with asymptomatic ponderosa pines and locations with pines presenting symptoms of deicing salt injury at 20 feet from the pavement edge (GLM in Appendix A-18).

Symptoms	N	Mean	SE	P
Asymptomatic	74	0.35	0.03	0.0120
Symptomatic	109	0.47	0.03	

The downslope soil samples had a significantly higher (P=0.0159) mean extractible sodium content than those upslope at 60 feet from the center line of the road (Appendix Table A-20), but this was the only distance where there was a significant difference in mean extractable soil sodium amounts.

High amounts of sodium can lead to a decrease in plant absorption of calcium and magnesium, two essential macronutrients. Soils saturated with sodium may increase in alkalinity and have a pH as high as 10 (Bryson and Barker, 2002). These pH changes can decrease the availability of certain micronutrients, most commonly iron and manganese, which can lead to plant deficiencies resulting in chlorotic foliage. Trahan and Peterson (2007) noted a significant difference in soil pH, as well as soil sodium, in the upper one foot of the soil between sample sites near the pavement edge and those 150 to 300 feet away. There was a significant difference in soil pH within the upper six inches of the soil between asymptomatic and symptomatic locations and distance from the road. The soil pH was highest adjacent to the road for all locations and highest for symptomatic locations (Table 5-26). The typical pH for the Pactola and Buska soils series in the upper 11 or 12 inches is between 5.6 and 7.3 (Ensz, 1990).

Table 5-26. Sample number (N), mean, and standard error of the means (SE) for comparisons of soil pH from 0 to 6 inches between locations with ponderosa pines exhibiting symptoms associated with deicing salts and asymptomatic locations at 3 and 20 feet from the pavement edge and 60 feet from the road centerline. (GLM in Appendix A-21).

Symptoms	Distance	N	Mean	SE
Asymptomatic	3 feet	8	7.52	0.07
	20 feet	8	7.33	0.16
	60 feet	8	6.69	0.15
Symptomatic	3 feet	8	7.97	0.05
	20 feet	8	7.47	0.15
	60 feet	8	6.99	0.15

Sodium amounts in soil are reported along with the sodium absorption ratio (SAR) (Table 5-27). This is a ratio of the amount cationic charge contributed by sodium compared to that of calcium and magnesium. Soils that have a SAR $\geq$ 13 are classified as sodic and the high sodium amounts in these soils can result in soil structure deterioration and water infiltration problems. The SAR for Buska and Pactola soil series is typically less than 1.0 (Radeke and Westin, 1963). In our study, there was a significant difference in SAR in the upper 6 inches of the soil with distance (P=0.0108) (Appendix Table A-22). However, SAR increased to between 2 and 3, much lower than the 13 to be considered sodic, an indication the additional amounts of sodium from deicing salts was not enough to result in changes to the soil structure. However, the SAR was still higher than normal at 3 and 20 feet from the pavement edge. At 60 feet from the road centerline the SAR was normal for these soil series.

Table 5-27. Sample number (N), mean, and standard error of the means (SE) for comparisons of soil Sodium Absorption Ratio for 0-6 inches soil depth at 3 and 20 feet from the pavement edge and 60 feet from the road centerline. (GLM in Appendix A-22).

Distance	N	Mean	SE
3 feet	16	2.63	0.64
20 feet	16	1.64	0.27
60 feet	16	0.65	0.09

The increased pH near the road is due to sodium displacing other elements as supported by the increase in SAR. The elevated pH is due to the presences of sodium bicarbonates.

The amount of soil sodium found at three feet from the road edge was higher than what normally occurs in Black Hills soils and the most likely explanation for this increase is deicing salt applications. The mean sodium amount at three feet was 0.82 meq/100 g, an amount high enough to cause injury to ponderosa pine, particularly seedlings. Whether this has caused injury in the Black Hills is unknown as there were no pines, seedling or otherwise, at this distance from the road at the sampling spots. Vegetation within this distance was mostly grasses and forbs.

5.4.5.2 Soil extractable Mg^{2+} amounts

Magnesium is released into the environment by the weathering of rock, primarily dolomite. The extractable soil magnesium amounts for this region generally range from near 0 to 0.83 meq/100 g, but may be as high as 1.4 to 2.3 meq/100 g in the upper three inches of forest soils in the Black Hills

(Kennedy et al., 1995). Forests with soil magnesium amounts between 0.9 and 3.9 meq/100 g have an adequate amount of this nutrient to support tree growth.

Extractable soil magnesium amounts from samples for this study ranged from a low of 0.3 meq/100 g to a high of 3.0 meq/100 g. Trahan and Peterson (2007) noted amounts of soil magnesium in the upper foot of the soil at 3.2 meq/100 g near the road edge in their Colorado study of their impact of deicing salts. However, these higher than normal amounts are not a cause of concern as magnesium is not toxic to vegetation, even at these amounts. The addition of magnesium to the soil can even improve soil structure (Lewis, 1999).

There was also a significant difference (*P*=0.0374) in the mean extractable soil magnesium with respect to distance from the road. The samples taken at three feet and 20 feet from the pavement edge had a higher amount of magnesium than those taken at 60 feet (Table 5-28).

Table 5-28. Sample number (N), mean, and standard error of the means (SE) for comparisons of amount (meg/100 g) of extractable soil magnesium (Mg^{2+}) for 0-24 inches at 3 and 20 from the pavement edge and 60 feet from the road centerline. (GLM in Appendix A-23).

Distance	N	Mean	SE
3 feet	185	0.24	0.03
20 feet	183	0.25	0.02
60 feet	185	0.18	0.02

There was also a significant difference in mean extractable soil magnesium amounts between asymptomatic and symptomatic locations at 20 feet from the edge of the pavement (Table 5-29). There was a significant difference (*P*=0.0433) in the mean soil magnesium amount with respect to depth but only at samples taken at 20 feet from the road edge (Appendix Table A-25).

Table 5-29. Sample number (N), mean, standard error of the means (SE), and P significance value (P) for comparisons of amount (meq/100 g) of extractable soil magnesium (Mg^{2+}) analysis between locations with asymptomatic ponderosa pines and locations with pines showing symptoms of deicing salt injury at 20 feet from the pavement edge (GLM in Appendix A-24).

Symptoms	N	Mean	SE	P
Asymptomatic	74	0.18	0.01	0.0008
Symptomatic	106	0.31	0.03	

5.4.5.3 Soil extractable Cl^- amounts

Extractable soil chloride amounts in the upper three inches of the soils in the Black Hills range from 0.05 to 0.26 meq/100 g (Kennedy et al. 1995). While there is very little soil data on desirable soil amounts of chloride, soil tests conducted away from coastal areas generally contain about 0.28 meq/100g or less. Chloride, a highly soluble anion, can quickly leach from the upper soil horizons during snow melt and spring rains (Viskari and Karenlampi, 2000). In this study the soil chloride amounts ranged from 0.03 to 0.33 meq/100 g. The mean for all sites and depth was 0.17 meq/100 g. Trahan and Peterson (2007) reported soil chloride concentrations between 3.02 and 7.94 meq/100 g for the upper foot of soil along roadside sites in the Denver, Colorado area. The pines on these Colorado sites also contained high foliage concentrations of chloride with a mean of 1.4 percent dry weight. However, numerous studies, including Trahan and Peterson (2007), were unable to correlate soil and foliage levels of chloride due to the mobility of the chloride ion in the soil.

Table 5-30. Sample number (N), mean, and standard error of the means (SE) for comparisons of amount (meg/ 100 g) of extractable soil chloride (Cl^-) for 0-24 inches at 3 and 20 from the pavement edge and 60 feet from the road centerline (GLM in Appendix A-26).

Distance	N	Mean	SE
3 feet	185	0.09	0.00
20 feet	183	0.19	0.02
60 feet	185	0.25	0.05

There was a significant difference (P=0.0024) in mean extractable soil chloride amounts with respect to distance (Table 5-30), but the direction of decrease differed from that of sodium and magnesium. Viskari and Karenlampi (2000) noted that soil chloride amounts decreased as the distance from the road increased, a trend similar to that of other deicing salt ions. However, chloride is very mobile and there was a steep slope on the downslope side of the road for the study locations. This resulted in an increase in the soil amount of chloride on the downslope side of the road for symptomatic locations (Figure 5-14). There was not a corresponding increase in foliage concentration of chloride, indicating that the increase in foliage concentration found in the pines on symptomatic locations was due to deicing salt aerial spray, not runoff from the road.

There was no significant difference between asymptomatic and symptomatic locations in mean soil chloride amounts (Table 5-31), orientation (Table 5-32), or depth (Table 5-33). The only significant difference was in mean extractable chloride amount for differing depths at three feet (P < 0.0001) and orientation (P=0.0111) (Appendix Table A-27). The soil at three feet from edge of pavement contained chloride at 0.05/mq/100g between a depth of 0 to 6 inches which increased to 0.13 meq/100 g at 12 to 24 inches. The close distance from the road edge increases the amount of chloride coming from the road surface as splash or spray. Chloride is very mobile and easily leaches so the amount decreases with depth.

Table 5-31. Sample number (N), mean, standard error of the means (SE), and P significance value (P) for comparisons of amount (meq/100 g) of extractable soil chlorine (Cl^-) analysis between locations with asymptomatic ponderosa pines and locations with pines showing symptoms of deicing salt injury (GLM in Appendix A-26).

Symptoms	N	Mean	SE	P
Asymptomatic	287	0.13	0.01	0.1060
Symptomatic	287	0.30	0.03	

Table 5-32. Sample number (N), mean, standard error of the means (SE), and P significance value (P) for comparisons of amount (meq/100 g) of extractable soil chlorine (Cl^-) analysis upslope or downslope from the road (GLM in Appendix A-26).

Orientation	N	Mean	SE	P
Downslope	287	0.20	0.01	0.0721
Upslope	287	0.14	0.01	

Table 5-33. Sample number (N), mean, standard error of the means (SE), and P significance value (P) for comparisons of amount (meq/100 g) of extractable soil chlorine (Cl^-) analysis at three sampling depths (GLM in Appendix A-26).

Depth	N	Mean	SE	P
0-6 inches	192	0.12	0.01	0.0684
6-12 inches	192	0.15	0.03	
12-24 inches	192	0.18	0.01	

5.4.5.4 Summary of soil nutrient amount analysis

The soils within three feet of the pavement edge contained the highest amounts of sodium and magnesium and these amounts decreased as the distance from the road increased (Figures 5-6 and 5-7). The amounts at three feet were higher than what is typically found in the region's soils. Soil sodium amounts at three feet from the road edge were high enough to result in injury to pine, particularly seedlings. The sodium amounts at 20 feet, while generally not high enough to injury pines were still higher than 60 feet where the amounts were within normal range. There was a significant difference in the mean extractible soil sodium amounts between pines at 20 feet from the pavement edge on asymptomatic and symptomatic locations. These patterns mirror that of the foliage where there was also a significant difference in the mean concentration of sodium between pines on asymptomatic and symptomatic locations.

Mean magnesium soil amounts also showed a significant difference with respect to distance from the road. However, no soil samples collected at any location or depth had amounts of this nutrient that were above that identified as even moderate in regards to soil fertility. There was a significant difference in the means of the extractible soil magnesium amounts at 20 feet from the pavement edge between asymptomatic and symptomatic locations.

Chloride, the deicing salt ion most associated with plant injury, also showed a change with distance. However, the amounts increased with distance only on the downslope side of the road (Figure 5-6 and 5-7). This is due to the mobility of the anion and in these channery soils the ion moves quickly with water flow. The trend in chloride was the opposite for canopies where the trees on the upslope had the highest concentration of chloride. The most likely source for the increased concentration of chloride in the foliage of pines at 20 feet from the pavement edge is chloride carried by aerial spray to the canopy rather than carried into the soil but run off and then absorbed into the tree. Low precipitation results in more chloride drying on the pavement as dust and later being carried into the canopies and deposited on the foliage where it remains to be absorbed rather than washed off during a storm.

The amount of deicing salts in soils generally decreases with distance from the road and soil depth. The rate of decrease is dependent upon the permeability of the soil and the chemical components of the deicing salt. Channery soils generally have moderate permeability with water moving at a rate of 0.6 to 2.0 inches per hour so highly mobile ions such as chloride are leached from the upper soil horizons (Adam, 2011). Chloride is considered to have the highest mobility followed by sodium with both of these ions being much more mobile than magnesium (Hudson, 1995).

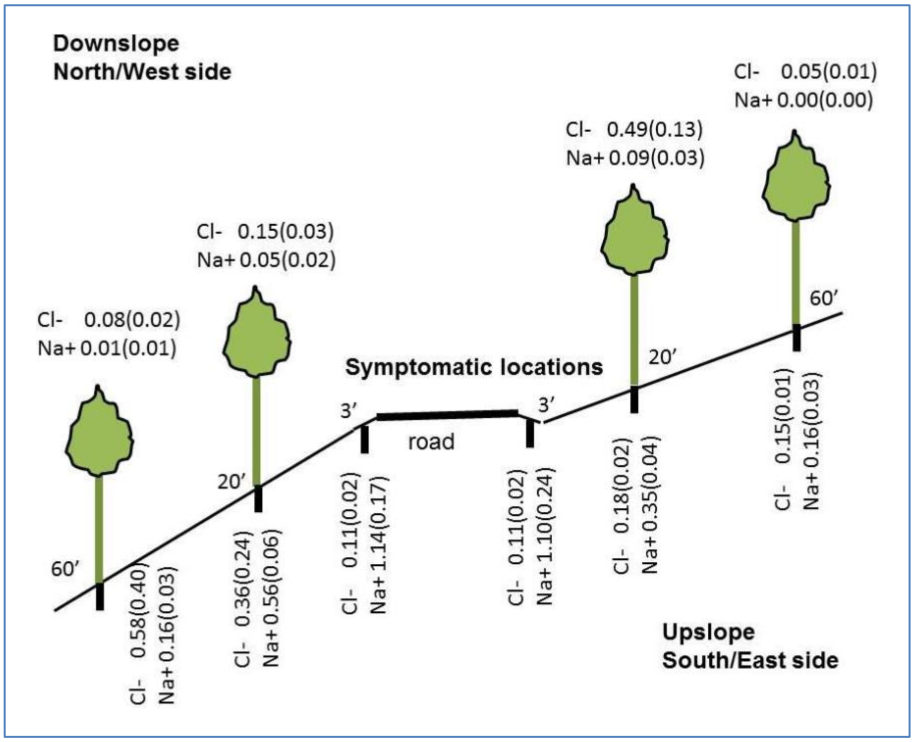

Figure 5-14. Mean (SE) foliage concentration and soil amounts (6-12 inch depth) for locations with ponderosa pines presenting symptoms of deicing salt injury.

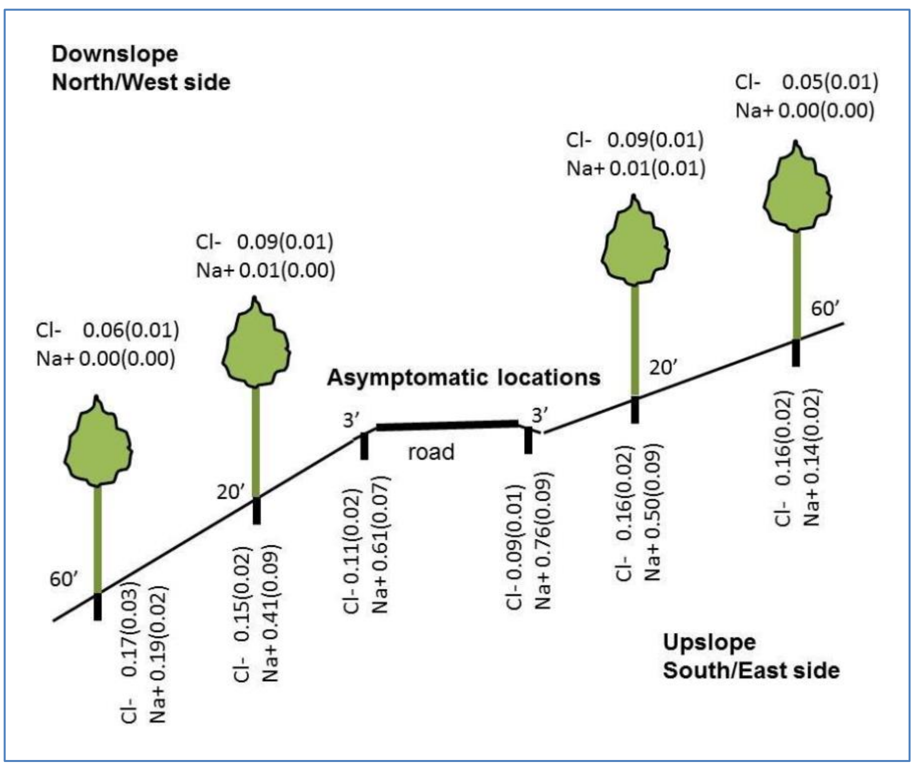

Figure 5-15. Mean (SE) foliage concentration and soil amounts (6-12 inch depth) for locations with ponderosa pines not presenting symptoms of deicing salt injury.

5.5 Other possible agents for the pattern of symptoms

Injury from deicing salts usually manifests in the lower exposed branches of the trees. Some ponderosa pines on the symptomatic sites possessed discolored foliage throughout the canopy of the tree. This is not a common symptom pattern for deicing salt injury where the vector is splash, though it can occur with aerial spray (Strong, 1944). However, this pattern of discoloration, as well as the appearance of necrotic spots in the needles, may also be associated with ozone (O_3) or drought.

5.5.1 Ozone

Ozone is an abiotic stressor that has been associated with discolored foliage and dieback in ponderosa pines, a species noted for its sensitivity to ozone (Evans and Miller, 1971). Ozone is an extremely damaging oxidant and a secondary pollutant caused by the action of ultraviolet radiation present in sunlight on hydrocarbons and oxides of nitrogen. While thunderstorms generate ozone naturally through electrical discharges, the primary source of its creation stems from anthropogenic activities using fossil fuels. Ozone is formed by reaction of volatile organic compounds (VOC) such as isoprene, a byproduct of photosynthesis, with nitrogen oxides (NO_x) emitted by coal burning power plants or automobiles. Elevated levels of NO_3^- in combination with the VOCs produced by pines can result in O_3 injury.

The EPA standard (US EPA, 1997) for ozone is the fourth highest, daily 8-hr average, averaged over three years. This is the derived from the highest of 17 consecutive 8-hour average (measured from 7:00 a.m. to 3:00 p.m. and 11:00 p.m. to 7 a.m.) and identifying the concentration at the fourth highest 8-hour daily maximum during the year. The fourth highest value for each of the three years is averaged. This is National Ambient Air Quality Standard primary standard, protection for public health, and the secondary standard, protection against damage to animals, crops, vegetation and buildings. Ozone is monitored by the EPA at several locations across the state. Wind Cave National Park had the highest three years (2006-2008) average of 0.073 ppm (South Dakota Department of Environment and Natural Resources, 2009).

A study was conducted in 2008 and 2009 to determine if O_3 levels in the Black Hills were high enough to injure the roadside ponderosa pines. The study was initiated when foliage necrotic spots and banding were observed on ponderosa pines along SD385, particularly in the areas near the Pactola Reservoir. Ozone injury is chlorotic mottling of the older foliage which may progress to premature needle abscission, branch dieback, and plant death (Miller et al., 1963). While these are common symptoms for pine foliage affected by ozone, similar symptoms can be attributed to deicing salt and drought injury.

Western snowberry (*Symphoricarpos occidentalis*), a woody shrub common as an understory species in the Black Hills and an ozone sensitive species was presenting similar symptoms. The symptoms appeared more severe near the road and there was the possibility that emissions from motor vehicles might provide sufficient precursors for the photochemical reactions that could result in phytotoxic ozone concentrations. The large influx of motorcycle traffic during the Sturgis Motorcycle Rally, an annually event held during the first full week of August that draws more than 400,000 motorcyclists and spectators, might be a source of high emissions. Although common O_3 precursors, nitrogen oxide from motor vehicle emissions, are higher near roadways, ozone concentrations are generally similar regionally with few changes within short distances. This is due to the photochemical reaction time necessary to generate ozone from the primary pollutants.

5.5.1.1 Ozone sampling results

Continuous ozone sampling with an active ozone monitor occurred from late May to mid-September 2008 at the summit of Veteran's Peak located near the town of Nemo and within the Black Hills National Forest (BHNF). Passive monitoring took place during the same period at six BHNF sites along US385 and one near the active site. During June 2008 the active monitor indicated several peaks in the "ozone damaging" range, but no prolonged high ozone levels occurred (Figure 5-16). Ozone injury is the level of ozone that causes foliar necrosis and/or chlorosis on pine needles. If the symptoms are severe enough to cause a visual impact to impair aesthetic value to forest visitors, the trees are ozone damaged (Musselman et al., 2006). However, the EPA's secondary standard, W126 index, is most often used for determining damage. This is the standard designed for protection to sensitive ecosystems including forests, parks and wilderness areas. Any level of ozone greater than the range of 7-15 ppm-hrs exceeds the standard for impact on this vegetation.

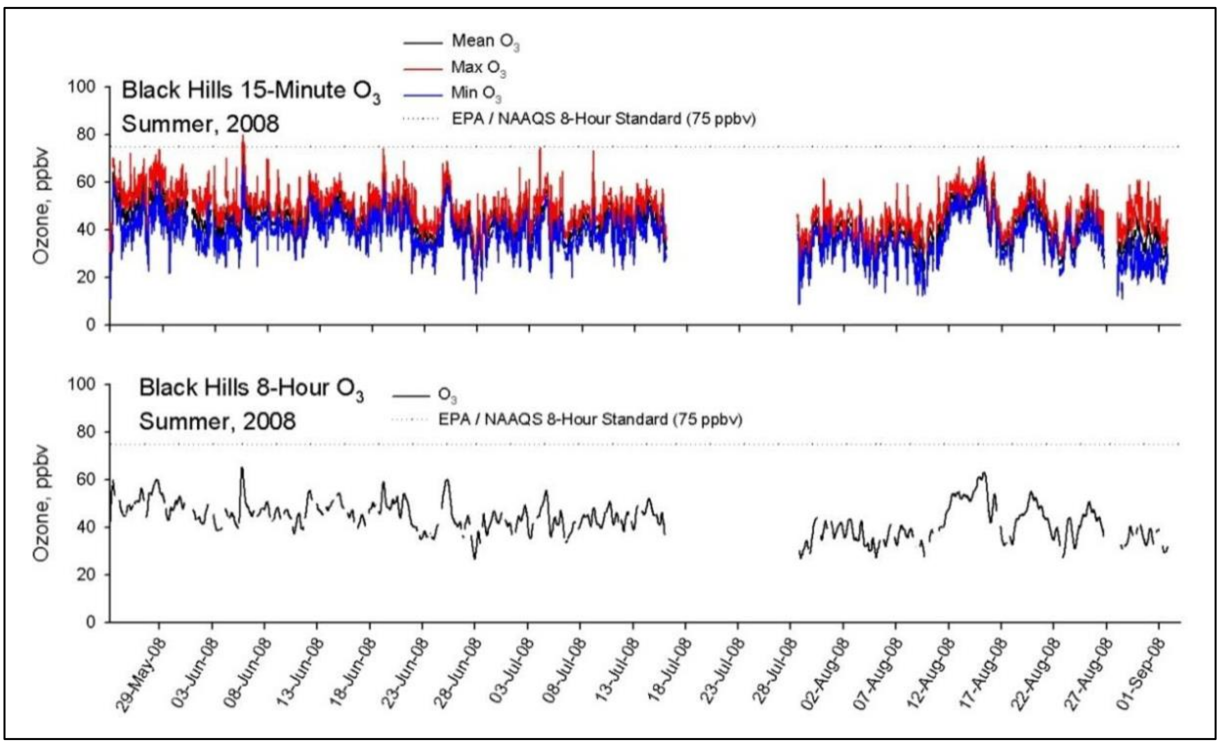

Figure 5-16. Continuous data from Vanocker Canyon Road hilltop ozone active monitoring site in 2008.

High levels of O_3 were expected during the summer due to increases in traffic flow, but a volunteer neglected to change the filter during their monthly visit, leading to a filter becoming plugged and the loss of continuous ozone data in July. Overall ozone concentrations in 2008 were below that of the National Ambient Air Quality Standard of 75 ppbv (0.075 ppm).

The 2009 ozone monitor season was similar in length to the 2008 season (Figure 5-17). The results of the 2009 passive ozone monitoring at several elevations near the Pactola Reservior and at differing heights in the canopies of pine trees showed little differences in nitrate concentrations in the passive sampler data.

Table 5-34. Nitrate (NO_3) concentrations (mg nitrate/hr) from passive ozone monitors at three different heights in a ponderosa pine canopy by exposure period.

Canopy	Exposure Period								
Height (ft)	1	2	3	4	5	6	7	8	9
6.5	0.013	0.009	0.010	0.012	0.010	0.012	0.012	0.013	0.010
16.5	0.016	0.010	0.010	0.013	0.010	0.012	0.012	0.013	0.011
26.5	0.016	0.010	0.010	0.013	0.011	0.013	0.013	0.014	0.011

Table 5-35. Nitrate (NO_3) concentrations (mg nitrate/hr) from the 2009 ozone monitors in the Black Hills National Forest.

	Exposure Period								
Monitor	1	2	3	4	5	6	7	8	9
Active monitor	0.016	0.009	0.011	0.013	0.011	0.013	0.012	0.014	0.013
Pactola canopy monitor	0.015	0.010	0.011	0.012	0.011	0.012	0.012	0.012	0.012
Passive monitor -hilliside	0.015	0.011	0.011	0.014	0.013	0.015	0.015	0.015	0.011
Passive monitor – near road	0.014	0.010	0.010	0.012	0.010	0.012	0.013	0.013	0.011

The similarity of data from the three different heights within the pine canopy suggests that the air impacting the sampler badges was well mixed (Table 5-33). Ozone consistently appeared to be slightly lower at the samplers within the canopy near the roadway than at those at the more open site up the hill. The open site with a greater fetch allowed O_3 to impact the sampler before being absorbed by foliage. Wet surfaces such as foliage can break down the O_3 molecule.

The ozone levels at the upper hilltop site were slightly higher than near the highway during most of the summer (Table 5-34). This may be a reflection of the elevation difference as the passive sampler loading values increase with elevation. The hilltop site was more than 320 feet higher in elevation than the highway site. Nevertheless, the similarity of data for the two passive samplers was expected, an indication that the upper hilltop and the highway sites were sampling the general air mass of the area.

Ozone appeared to be higher during the first exposure period in mid-May 2009 than during any other time during that growing season. The passive data did not indicate any higher values during the Sturgis Motorcycle Rally. Passive samplers record continuous loading and cumulative exposure and thus were unable to determine whether high NO_3 values found from the passive filter analyses are from a large number of low O_3 events or a few high-value O_3 episodic events during this exposure period. Data from the continuous monitor indicates that the U.S. National Ambient Air Quality Standard (NAAQS) for O_3 prior to 2008 (Primary Standard of 84 ppb per 8-hour average) and 2008-2009 NAAQS (Primary Standard of 75 ppb per 8-hour average) (US EPA, 2008) were likely not exceeded at the Pactola Reservoir monitoring site (Figure 5-17).

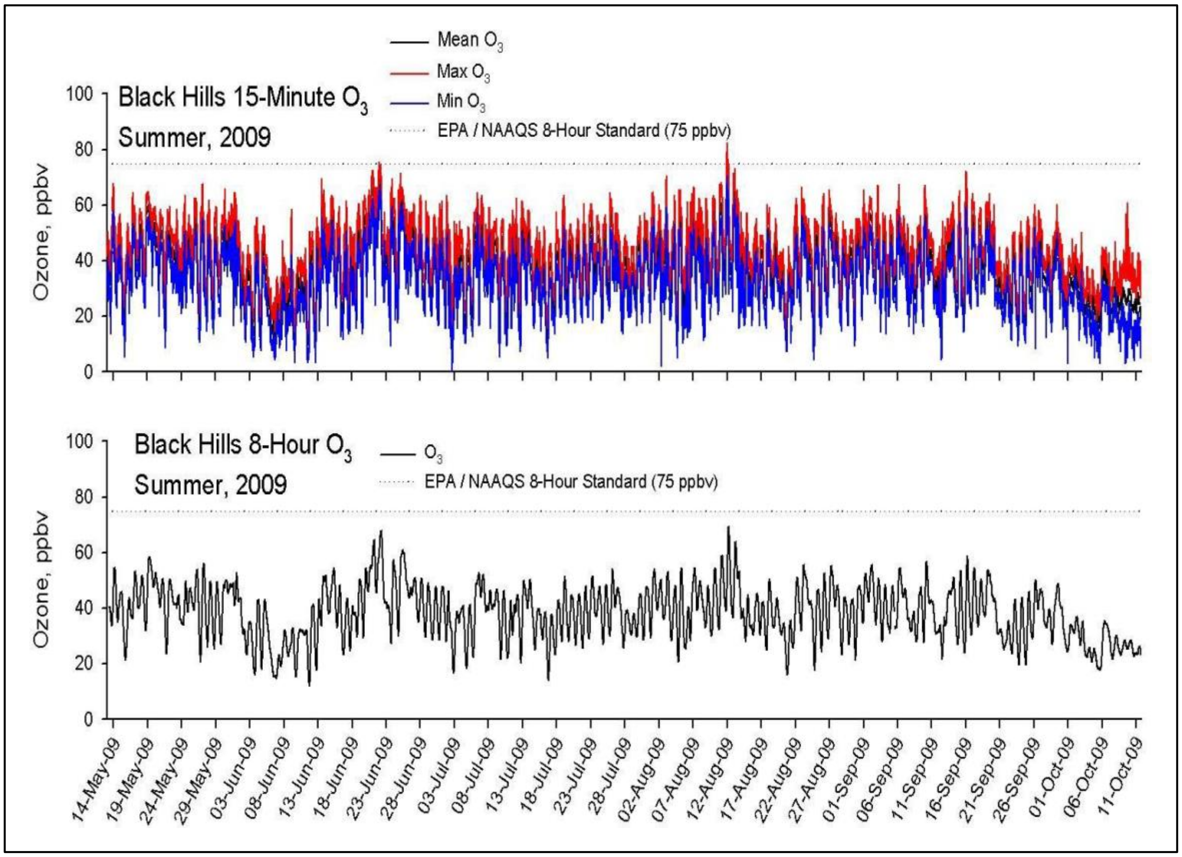

Figure 5-17. Continuous data from the Pactola ozone active monitoring site in 2009.

The EPA also proposed Secondary Standard "designed to protect sensitive vegetation and ecosystems, including forests, parks, wildlife refuges and wilderness areas" but it was withdrawn in 2010 (U.S. EPA, 2011). The proposed, but withdrawn, Secondary Standard used a cumulative parameter, the W126 metric, which preferentially weights higher concentration since these have a greater impact on vegetation. The W126 weighted value is expressed as a sum on weighted hourly concentrations, cumulated from 8:00 a.m. to 8:00 p.m. The W126 hourly values are summed for each day and accumulated for each month. The monthly values are summed to obtain the highest seasonal three-month cumulative W126 value. The proposed Secondary Standard stated that the W126 seasonal cumulative value should not exceed 7-15 ppm-hrs. The cumulative W126 values was 5.11 ppm-hrs for the three-month period from July through September. This means the ozone concentrations in the area were not high enough in either 2008 or 2009 to be responsible for the foliar symptoms on ponderosa pine foliage.

Table 5-36. Ozone levels and temperatures observed at the Pactola Reservoir monitoring site.

Dates (2009)	Time Period	Mean Temp (ºF)	Mean T_{max} (ºF)	Mean O_3 (ppb)	Max 8-hour O_3 (ppb)	Mean Radiation (W/m^2)	Max Radiation (W/m^2)	Radiation Flux ($kW\text{-}hr/m^2/day$)
June 22	Near Solstice	68.90	80.60	58.7	67.7	616.5	1088	157.8
July 27—August 2	Before Rally	62.24	75.74	39.6	54.3	415.5	1024	104.5
August 3—August 9	Sturgis Rally	65.66	81.68	40.2	54.6	414.3	1033	89.7
August 10—August 16	After Rally	65.66	81.32	43.8	69.7	396.9	1004	85.9
Solar radiation data are from the Baker Park RAWS site, on the east shore of Sheridan Lake about 8 miles (12.8 km) south/southeast of Pactola Reservoir								

The data shows higher O_3 values during mid-August, after the Sturgis Motorcycle Rally. Similar higher values were observed the last half of June. Highest W126 values were in August and the second highest in June. Hot, dry weather conditions favor formation of ambient O_3 and this can sometimes explain difference in O_3 levels. However, our temperature data suggest that mean and maximum daily temperatures following the Rally were nearly the same as those during Rally week (Table 5-36).

Considering the popularity of the Rally it was expected that the ozone levels would have been higher during, rather than following it. Perhaps the traffic, combination of motorcycles, cars and recreational vehicles, may have been higher the following week but we have no traffic data to determine whether this is true. Ozone values were also high the second half of June, however, this was closer to the solstice when longer days allow for greater opportunities for photochemical generation of O_3.

5.5.2 Drought

Deicing salt injury on pines appears as discoloration of foliage typically in the lower canopy and the side facing the highway. The needles are often yellow at the tips with an abrupt transition between the dead and green portion. Many of the pines identified as symptomatic also had discolored foliage in the upper canopies and exhibited dieback. This is a common pattern of symptoms observed with drought stress (Miller, 1993). The symptoms of drought on pines begin in the upper canopy and the outer branch tips and gradually spread lower into the canopy and the interior as the drought persists. Pines affected by drought also will have early senescence and abscission of the needles, with many of the third-year needles falling prematurely (Sinclair and Lyon, 2005).

The Black Hills experienced a drought for much of the decade of 2001-2010 with normal summer precipitation only returning in 2008. May and June are generally the wettest months of the year and may account for more than one-third of the total annual precipitation (Driscoll et al., 2000). The April to June precipitation from 2004 through 2007 was generally about 75 percent of the long-term average with 2008 to 2010 being above normal (Table 5-36). Since 2008 the general color of the pines along the highways has improved. Some study sites that had pines exhibited symptoms associated with deicing salts became asymptomatic by 2010. The reduction in the trees exhibiting discolored foliage from the 2007 survey and the 2011 survey is striking (Table 5-3). The drought was ending for most the Black Hills by 2008 and the trees recovered from the drought stress very quickly.

One interesting observation from the survey is that the appearance of the pines in the area between Custer State Park and Mount Rushmore (the area including SD40 and SD87) did not improve and on some survey points greater discoloration was observed. The Needles Highway, SD87, between county road 753 and SD89, is closed during the winter and does not receive deicing salt. However, some of the pines along this highway were also presenting yellow needles and canopy dieback. Some of this was due to the mountain pine beetle epidemic as pine mortality by this insect increased in this area between 2007 and 2011. The other reason is that the soils in the area of the Needles are very rocky and shallow and drought recovery can take considerably longer.

Table 5-37. April to June precipitation (inches) for two communities in the Black Hills of South Dakota.

Year	Custer	Rapid City
2001	9.03	9.54
2002	6.57	6.05
2003	7.89	6.38
2004	4.01	5.76
2005	7.50	7.81
2006	6.49	6.36
2007	7.24	6.82
2008	12.03	14.92
2009	9.02	10.98
2010	12.91	12.48

The drought played a significant role in the poor appearance of the pines along the highways of the Black Hills for two reasons:

1) The low precipitation stressed pines throughout the Black Hills. The April to June period is when most active growth occurs on pines so trees are most sensitive to water deficits during this time. The older foliage also became discolored and is shed prematurely which results in more open canopies.

2) The low precipitation during the April to June can also aid in the spread and absorption of salt into the trees. A spring drought increases the amount of salt left on the roadway as dust. This dried salt crust is dislodged by the tire-road interface and updrafts generated by the vehicular traffic causes redistribution of the deicer into the tree canopy (Hautula et al., 1995; Williams et al., 2000). Dry deposition of the aerosol can result in foliage injury from the direct uptake of chloride into the needles (Aamlid and Horntvedt, 2001).

Drought, as with ozone or deicing salts, is seldom the sole stressor and the combination of these agents can result in more injury than one acting alone. Drought injury, for example, is more severe when coupled with other stressors such as deicing salts, so drought and deicing salt applications in combination can result in more injury than either alone. The amount of chloride detected in the foliage of the pines on symptomatic sites 20 feet from the pavement was generally close to the lower limit of concentrations known to produce symptoms in pines. During years with normal or above normal spring and summer precipitations, the same amount of salt applied to the road may not have resulted in symptoms.

During dry summers, needle stomata, the pore through which gas exchange occurs, may close due to low soil moisture. Volatiles emitted through the foliage are a major contributor to the formation of ozone (Donahue et al, 2012). This result in lower ozone concentrations since the plants are emitting fewer volatiles (Bauer et al., 2012). A Colorado study on the effects of ozone and climate on ponderosa pine concluded that the ozone concentrations detected during the monitoring, which were only slightly higher than those detected in our study, were not responsible for the reduction in growth. Decline was instead attributed to reduced spring and early summer precipitation (Peterson et al., 1993).

6 IMPLEMENTATION RECOMMENDATIONS

The discoloration and dieback of pines along the state highways in the Black Hills were due to two stress agents, road deicing salt and drought. Concentrations of deicing salts, specifically chloride, were high enough in the foliage of the symptomatic pines at 20 feet from the pavement edge to cause the discoloration and dieback of these trees. However, since the appearance of many trees on the symptomatic sites improved by the conclusion of the study, the most likely predisposing stress agent was the drought that ended in 2008. The trees' response to these two stressors is similar and the two in combination can create more injury than either one. Low precipitation also aided the spread and absorption of salt into the trees. Salt that dries on the pavement can be dislodged by the tire-road interface and updrafts generated by the vehicular traffic redistribute the deicer into the environment. The dry deposition of the aerosol can result in foliage injury due to the direct uptake of chloride into the needles.

Based upon the findings of this study, SDDOT should consider four recommendations.

6.1 Track Deicer Use

SDDOT should develop mechanisms to report and track salt use data by unit, snow route, and truck.

Rapid City and Custer units of SDDOT were unable to provide accurate documentation regarding the quantity of deicing salts they applied during the study period. We recommend that the SDDOT adopt a deicing salt dispersal system for their vehicles that can monitor and quantify the amounts of deicing salt used. This will be a very valuable means of measuring the reduction in salt use on the roads and more accurately adjusting application rates to road condition.

The South Dakota Department of Transportation lead a multi-state pooled fund study that was completed in 2012, after the data collection of this study was completed. The MDSS uses time- and location-specific weather forecasts and computer modeling of weather, pavement, traffic, and maintenance to optimize the type and timing of winter maintenance treatments. Snowplows are equipped with instrumentation that tracks vehicle location, measures air and road temperature, and reports operators' visual observations of road condition, plowing activity and the type and application rate of deicing material applied to the roadway. The adoption of automatic vehicle location (AVL)/ global positioning system (GPS) is a key component of MDSS. The implementation of MDSS by the Indiana Department of Transportation during one winter resulted in a reduction of 228,470 tons of salt, about 40 percent less deicing salts from the previous year (McClellan et al., 2009).

The deployment of the AVL/GPS which monitors weather/road conditions and salt appplications as part of the MDSS fulfill this recommendation.

6.2 Reduce Chloride Use

SDDOT should reduce the use of chloride along roadways in the Black Hills.

Ponderosa pine is the dominant species in the Black Hills forest and the most common tree found along the highways. It is also the most sensitive to road deicing salts of the native trees in the region and the only species in which we saw injury. The roadways that have ponderosa pines within 60 feet of the centerline is where the reduction in deicing salts is needed. This is about two-thirds of the total roadway length in the Black Hills.

Chloride is the component in deicing agents responsible for vegetation injury and any delivery system that reduces the amount applied on the roads will be beneficial to the health and appearance of the roadside vegetation. Chloride reduction can be accomplished by reducing the amount of chloride used in deicing operations, using direct liquid applications of deicing salts, and pre-wetting dry deicing materials as they are applied to the roadway. Direct application of salt brine, rather than a solid, can reduce chloride applications rates by half (Fay, et. al., 2013). Pre-wetting can increase the performance and retention of solid chemicals and abrasives on the pavement and reduce chloride applications rates by 10 percent (o'Keefe and Shi, 2006).

Since the completion of this study, the SDDOT has switched from using a salt/sand mixture to salt and a salt brine. They are also using liquid magnesium chloride in select locations. These practices fulfill this recommendation.

6.3 Reduce Winter Speed Limits

SDDOT should consider reducing winter driving speed limits in the Black Hills.

The amount of chloride carried into the ponderosa pine canopies and absorbed by the foliage depends on the application amount, the precipitation during late winter to late spring, and the volume and speed of the traffic. Only two factors—the amount of chloride applied and the speed of the traffic—lie within the control of the SDDOT. Updrafts generated by vehicular traffic redistribute deicing agents into the environment beyond the road. Highway speeds between 50 and 55 miles per hour have been shown to carry deicing salts to distances of 15 to 25 feet from the pavement edge. We were able to find foliage injury due to chloride concentration on the pines at 20 feet on symptomatic sites. Reducing the speed of the traffic can reduce the distance of potential plant damage (Blomqvist and Johansson, 1999). While relatively few studies have investigated vehicular speed and deicing salts, a reduction from 55 to 40 miles per hour could possibly reduce the amount of road salt carried beyond the pavement by one-third.

This reduction would be only along lengths of roadway that have ponderosa pines within 60 feet of the road centerline. This is about two-thirds of the road system.

6.4 Maintain Trees Near the Roadway

SDDOT should, wherever possible, maintain trees at 30 feet from the pavement edge in the Black Hills.

The mountain pine beetle epidemic in the Black Hills resulted in thousands of acres of dead ponderosa pines. Infested and dead trees within 60 feet of the highway were a fall hazard to traffic and most of these trees have been removed. The USDA Forest Service also increased thinning programs on the lands they managed to reduce the susceptibility to mountain pine beetle attack. The result of these efforts is a decrease in pines within 60 feet of the road during the 2010s. The highest concentrations of deicing salts in our study were found at three feet from the edge of the road and concentrations of ions in the foliage and the amounts in the soil significantly decreased at 20 feet and were within concentrations and amounts considered normal by 60 feet. Several studies have noted that the distance of injury increases in open meadows compared to dense forests (Hofstra and Hall, 1971). Maintaining tree cover at 30 feet from the road may reduce injury farther into the forest. We encourage maintaining healthy mature pines within this area to limit the potential spread of salt farther into the environment.

7 ANALYSIS OF RESEARCH BENEFITS

This study provides specific recommendations for future management of deicing salts in the Black Hills of South Dakota. These recommendations are based upon a survey of the highway system in the Black Hills and collection of data on roadside woody vegetation presence and condition, analysis of soils and foliage at various sites, ozone monitoring and interviews with SDDOT personnel regarding current deicing salt compounds and practices.

The primary benefit of this study is the confirmation that deicing salt practices likely were responsible for discoloration and decline of pines along the highways in the Black Hills. However, the concentrations of chloride and sodium in the foliage of symptomatic trees were within the lower limits for causing injury. The drought that occurred during the study time period was another stressor that caused similar symptoms and the two in combination could result in more injury than either alone. The same deicing practices during years of normal or above-normal precipitation may have resulted in less visible injury.

The benefit to following the recommendations outlined in this report will be reducing the potential detrimental effects of deicing salts on roadside vegetation. Reduction in the amount of chloride applied to the road, reducing the speed of traffic, and maintaining trees as buffers will limit the spread of chloride into the roadside environment.

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APPENDIX A SUPPORTING ANALYSIS

Table A-1. The TTEST Procedure for foliage sodium (Na) concentration in ponderosa pines 20 feet from the pavement edge on asymptomatic and symptomatic locations.

Symptom	Method	Mean	95% CL Mean		Std Dev	95% CL Std Dev	
Asymptomatic		0.00969	0.00473	0.0145	0.0137	0.0110	0.0183
Symptomatic		0.0706	0.0326	0.1085	0.1052	0.08440	0.1399
Diff (1-2)	Pooled	-0.0609	-0.0984	-0.0234	0.0750	0.0638	0.0910
Diff (1-2)	Satterthwaite	-0.0609	-0.0991	-0.0227			

Method	Variances	DF	t Value	Pr > t
Pooled	Equal	62	-3.25	0.0019
Satterthwaite	Unequal	32.056	-3.25	0.0027

	Equality of Variances			
Method	Num DF	Den DF	F Value	Pr >F
Folded F	31	31	58.67	<0.0001

Table A-2. The TTEST Procedure for foliage sodium (Na) concentration in ponderosa pines 20 feet from the pavement edge and 60 feet from the road centerline on symptomatic locations.

Distance	Method	Mean	95% CL Mean		Std Dev	95% CL Std Dev	
20 feet		0.0706	0.0326	0.1085	0.1052	0.08440	0.1399
60 feet		0.00824	-0.00273	0.0192	0.0304	0.0244	0.0404
Diff (1-2)	Pooled	0.0623	0.0236	0.1010	0.0775	0.0659	0.0940
Diff (1-2)	Satterthwaite	0.0623	0.0231	0.1016			

Method	Variances	DF	t Value	Pr > t
Pooled	Equal	62	3.22	0.0020
Satterthwaite	Unequal	36.143	3.22	0.0027

	Equality of Variances			
Method	Num DF	Den DF	F Value	Pr >F
Folded F	31	31	11.97	<0.0001

Table A-3. The TTEST Procedure for foliage sodium (Na) concentration in ponderosa pines 20 feet from the pavement edge and 60 feet from the road centerline on asymptomatic locations.

Distance	Method	Mean	95% CL Mean		Std Dev	95% CL Std Dev	
20 feet		0.00969	0.00473	0.0146	0.0137	0.0110	0.0183
60 feet		0.00381	0.00200	0.00562	0.0103	0.00880	0.00668
Diff (1-2)	Pooled	0.00587	0.000705	0.0110	0.0103	0.00880	0.0125
Diff (1-2)	Satterthwaite	0.00587	0.000644	0.0111			

Method	Variances	DF	t Value	Pr > t
Pooled	Equal	62	2.27	0.0266
Satterthwaite	Unequal	39.157	2.27	0.0287

	Equality of Variances			
Method	Num DF	Den DF	F Value	Pr >F
Folded F	31	31	7.47	<0.0001

Table A-4. The TTEST Procedure foliage sodium (Na) concentrations (percent dry weight) for ponderosa pines on asymptomatic locations at 20 feet from the pavement edge by sampling season.

Season	N	Means	Std Dev	Std Error	Minimum	Maximum
Autumn	16	0.0066	0.0096	0.0024	0.0010	0.0349
Spring	16	0.0128	0.0166	0.0042	0.0010	0.0642
Diff (1-2)		-0.0063	0.0136	0.0048		

Season	Method	Mean	95% CL Mean		Std Dev	95% CL Std Dev	
Autumn		0.0066	0.0014	0.0117	0.0096	0.0071	0.0149
Spring		0.0128	0.0040	0.0217	0.0166	0.0123	0.0257
Diff (1-2)	Pooled	-0.0063	-0.0161	0.0036	0.0136	0.0109	0.0182
Diff (1-2)	Satterthwaite	-0.0063	-0.0162	0.0036			

Method	Variances	DF	t Value	Pr > t
Pooled	Equal	30	-1.3	0.2030
Satterthwaite	Unequal	39.157	2.27	0.0287

	Equality of Variances			
Method	Num DF	Den DF	F Value	Pr >F
Folded F	15	15	2.98	0.0419

Table A-5. The TTEST Procedure foliage sodium (Na) concentrations (percent dry weight) for ponderosa pines on symptomatic locations at 20 feet from the pavement edge by sampling season.

Season	N	Means	Std Dev	Std Error	Minimum	Maximum
Autumn	16	0.0481	0.0869	0.0217	0.0013	0.2630
Spring	16	0.0930	0.1194	0.0299	0.0010	0.3137
Diff (1-2)		-0.0448	0.1044	0.0369		

Season	Method	Mean	95% CL Mean		Std Dev	95% CL Std Dev	
Autumn		0.0048	0.0019	0.0944	0.0096	0.0071	0.0149
Spring		0.0930	0.0294	0.1566	0.0166	0.0123	0.0257
Diff (1-2)	Pooled	-0.0448	-0.1203	0.0306	0.1044	0.0835	0.1396
Diff (1-2)	Satterthwaite	-0.0448	-0.1206	0.0309			

Method	Variances	DF	t Value	Pr > t
Pooled	Equal	30	-1.21	0.2340
Satterthwaite	Unequal	27.402	-1.21	0.2349

	Equality of Variances			
Method	Num DF	Den DF	F Value	Pr >F
Folded F	15	15	1.89	0.2292

Table A-6. The TTEST Procedure for foliage magnesium (Mg) concentration in ponderosa pines 20 feet from the pavement edge on asymptomatic and symptomatic locations.

Symptom	Method	Mean	95% CL Mean		Std Dev	95% CL Std Dev	
Asymptomatic		0.1236	0.1131	0.1341	0.0290	0.0232	0.0385
Symptomatic		0.1281	0.01182	0.1381	0.0276	0.0221	0.0366
Diff (1-2)	Pooled	-0.00452	-0.0187	0.00962	0.0283	0.0241	0.0343
Diff (1-2)	Satterthwaite	-0.00452	-0.0187	0.00962			

Method	Variances	DF	t Value	Pr > t
Pooled	Equal	62	-0.64	0.5251
Satterthwaite	Unequal	61.842	-0.64	0.5251

	Equality of Variances			
Method	Num DF	Den DF	F Value	Pr >F
Folded F	31	31	1.11	0.7802

Table A-7. The TTEST Procedure for foliage magnesium (Mg) concentration in ponderosa pines 20 feet from the pavement edge and 60 feet from the road centerline on symptomatic locations.

Distance	Method	Mean	95% CL Mean		Std Dev	95% CL Std Dev	
20 feet		0.1281	0.1182	0.1381	0.0276	0.0221	0.0366
60 feet		0.1291	0.1206	0.1375	0.0235	0.0188	0.0312
Diff (1-2)	Pooled	-0.00095	-0.0137	0.0118	0.0256	0.0218	0.0311
Diff (1-2)	Satterthwaite	-0.00095	-0.0137	0.0118			

Method	Variances	DF	t Value	Pr > t
Pooled	Equal	62	-0.15	0.8825
Satterthwaite	Unequal	60.47	-0.15	0.8825

	Equality of Variances			
Method	Num DF	Den DF	F Value	Pr >F
Folded F	31	31	1.38	0.3766

Table A-8. The TTEST Procedure for foliage magnesium (Mg) concentration in ponderosa pines 20 feet from the pavement edge and 60 feet from the road centerline on asymptomatic locations.

Distance	Method	Mean	95% CL Mean		Std Dev	95% CL Std Dev	
20 feet		0.1236	0.1131	0.1341	0.0290	0.0232	0.0385
60 feet		0.1201	0.1095	0.1307	0.0294	0.0236	0.0391
Diff (1-2)	Pooled	0.00351	-0.0111	0.0181	0.0292	0.0248	0.0354
Diff (1-2)	Satterthwaite	0.00351	-0.0111	0.0181			

Method	Variances	DF	t Value	Pr > t
Pooled	Equal	62	0.48	0.6326
Satterthwaite	Unequal	61.988	0.48	0.6326

	Equality of Variances			
Method	Num DF	Den DF	F Value	Pr >F
Folded F	31	31	1.03	0.9395

Table A-9. The TTEST Procedure foliage magnesium (Mg) concentrations (percent dry weight) for ponderosa pines on asymptomatic locations at 20 feet from the pavement edge by sampling season.

Season	N	Means	Std Dev	Std Error	Minimum	Maximum
Autumn	16	0.1285	0.0317	0.0079	0.0853	0.2144
Spring	16	0.1187	0.0261	0.0065	0.0700	0.1743
Diff (1-2)		0.0098	0.0290	0.0103		

Season	Method	Mean	95% CL Mean		Std Dev	95% CL Std Dev	
Autumn		0.1285	0.1116	0.1454	0.0317	0.0234	0.0491
Spring		0.1187	0.1048	0.1326	0.0261	0.0192	0.0403
Diff (1-2)	Pooled	0.0098	-0.0112	0.0307	0.0290	0.0232	0.0388
Diff (1-2)	Satterthwaite	0.0098	-0.0112	0.0308			

Method	Variances	DF	t Value	Pr > t
Pooled	Equal	30	0.95	0.3492
Satterthwaite	Unequal	28.903	0.95	0.3494

	Equality of Variances			
Method	Num DF	Den DF	F Value	Pr >F
Folded F	15	15	1.48	0.4538

Table A-10. The TTEST Procedure foliage magnesium (Mg) concentrations (percent dry weight) for ponderosa pines on symptomatic locations at 20 feet from the pavement edge by sampling season.

Season	N	Means	Std Dev	Std Error	Minimum	Maximum
Autumn	16	0.1250	0.0253	0.0063	0.0913	0.1814
Spring	16	0.1312	0.0301	0.0075	0.0855	0.2100
Diff (1-2)		-0.0062	0.0278	0.0098		

Season	Method	Mean	95% CL Mean		Std Dev	95% CL Std Dev	
Autumn		0.1250	0.1115	0.1385	0.0253	0.0187	0.0392
Spring		0.1312	0.1152	0.1473	0.0301	0.0223	0.0467
Diff (1-2)	Pooled	-0.0062	-0.0263	0.0139	0.0278	0.0222	0.0372
Diff (1-2)	Satterthwaite	-0.0062	-0.0263	0.0139			

Method	Variances	DF	t Value	Pr > t
Pooled	Equal	30	-0.63	0.5326
Satterthwaite	Unequal	29.123	-0.63	0.5327

	Equality of Variances			
Method	Num DF	Den DF	F Value	Pr >F
Folded F	15	15	1.42	0.5054

Table A-11. The TTEST Procedure for foliage chloride (Cl) concentration in ponderosa pines 20 feet from the pavement edge on asymptomatic and symptomatic locations.

Symptom	Method	Mean	95% CL Mean		Std Dev	95% CL Std Dev	
Asymptomatic		0.0902	0.0761	0.1043	0.0391	0.0314	0.0520
Symptomatic		0.3182	0.1748	0.4619	0.3981	0.3191	0.592
Diff (1-2)	Pooled	-0.2282	-0.3695	-0.0868	0.02828	0.2406	0.03431
Diff (1-2)	Satterthwaite	-0.2282	-0.3723	-0.0841			

Method	Variances	DF	t Value	Pr > t
Pooled	Equal	62	-3.23	0.0020
Satterthwaite	Unequal	31.599	-3.23	0.0029

	Equality of Variances			
Method	Num DF	Den DF	F Value	Pr >F
Folded F	31	31	103.57	,0.0001

Table A-12. The TTEST Procedure for foliage chloride (Cl) concentration in ponderosa pines 20 feet from the pavement edge and 60 feet from the road centerline on symptomatic locations.

Distance	Method	Mean	95% CL Mean		Std Dev	95% CL Std Dev	
20 feet		0.3183	0.1748	0.4619	0.3981	0.3191	0.5292
60 feet		0.0641	0.0424	0.0857	0.0601	0.0482	0.0799
Diff (1-2)	Pooled	0.2543	0.1120	0.3965	0.2847	0.2422	0.3453
Diff (1-2)	Satterthwaite	0.2543	0.1094	0.3992			

Method	Variances	DF	t Value	Pr > t
Pooled	Equal	62	3.57	0.0007
Satterthwaite	Unequal	32.412	3.57	0.0011

	Equality of Variances			
Method	Num DF	Den DF	F Value	Pr >F
Folded F	31	31	43.88	<0.0001

Table A-13. The TTEST Procedure for foliage chloride (Cl) concentration in ponderosa pines 20 feet from the pavement edge and 60 feet from the road centerline on asymptomatic locations.

Distance	Method	Mean	95% CL Mean		Std Dev	95% CL Std Dev	
20 feet		0.0902	0.0761	0.1043	0.0391	0.0314	0.0520
60 feet		0.0562	0.0464	0.0661	0.0273	0.0219	0.0363
Diff (1-2)	Pooled	0.0339	0.0171	0.0508	0.0337	0.0287	0.0409
Diff (1-2)	Satterthwaite	0.0339	0.0170	0.0508			

Method	Variances	DF	t Value	Pr > t
Pooled	Equal	62	4.02	0.0002
Satterthwaite	Unequal	55.406	4.02	0.0002

	Equality of Variances			
Method	Num DF	Den DF	F Value	Pr >F
Folded F	31	31	2.05	0.0493

Table A-14. The TTEST Procedure for foliage chloride (Cl) concentration in ponderosa pines 20 feet from the pavement edge on symptomatic locations by orientation.

Orientation	Method	Mean	95% CL Mean		Std Dev	95% CL Std Dev	
Downslope		0.1477	0.0944	0.2010	0.1001	0.0739	0.1549
Upslope		0.4890	0.2197	0.7582	0.5053	0.3733	0.7821
Diff (1-2)	Pooled	-0.3412	-0.6043	-0.0782	0.3642	0.2911	0.4869
Diff (1-2)	Satterthwaite	-0.3412	-0.6140	-0.0685			

Method	Variances	DF	t Value	Pr > t
Pooled	Equal	30	-2.65	0.0127
Satterthwaite	Unequal	16.175	-2.65	0.0174

	Equality of Variances			
Method	Num DF	Den DF	F Value	Pr >F
Folded F	15	15	25.50	<0.0001

Table A-15. The TTEST Procedure foliage chloride (Cl) concentrations (percent dry weight) for ponderosa pines on asymptomatic locations at 20 feet from the pavement edge by sampling season.

Season	N	Means	Std Dev	Std Error	Minimum	Maximum
Autumn	16	0.0923	0.03331	0.0083	0.0482	0.1512
Spring	16	0.0880	0.0454	0.00113	0.0274	0.1740
Diff (1-2)		0.0397	0.0397	0.0140		

Season	Method	Mean	95% CL Mean		Std Dev	95% CL Std Dev	
Autumn		0.0923	0.0747	0.1100	0.0331	0.02440	0.0512
Spring		0.0880	0.0638	0.1121	0.0454	0.0335	0.0702
Diff (1-2)	Pooled	0.0044	-0.0243	0.0330	0.0397	0.0317	0.0531
Diff (1-2)	Satterthwaite	0.0044	-0.0244	0.0331			

Method	Variances	DF	t Value	Pr > t
Pooled	Equal	30	0.31	0.7576
Satterthwaite	Unequal	27.424	0.31	0.7578

	Equality of Variances			
Method	Num DF	Den DF	F Value	Pr >F
Folded F	15	15	1.88	0.2315

Table A-16. The TTEST Procedure foliage chloride (Cl) concentrations (percent dry weight) for ponderosa pines on symptomatic locations at 20 feet from the pavement edge by sampling season.

Season	N	Means	Std Dev	Std Error	Minimum	Maximum
Autumn	16	0.2801	0.3423	0.0856	0.0602	1.4691
Spring	16	0.3566	0.4551	0.1138	0.0342	1.6650
Diff (1-2)		-0.0764	0.4027	0.1424		

Season	Method	Mean	95% CL Mean		Std Dev	95% CL Std Dev	
Autumn		0.2801	0.0977	0.4625	0.3423	0.2529	0.5298
Spring		0.3566	0.1140	0.5991	0.4551	0.3362	0.7044
Diff (1-2)	Pooled	-0.0764	-0.3672	0.2143	0.4027	0.3218	0.5383
Diff (1-2)	Satterthwaite	-0.0764	-0.3681	0.2153			

Method	Variances	DF	t Value	Pr > t
Pooled	Equal	30	-0.54	0.5953
Satterthwaite	Unequal	27.857	-0.54	0.5956

	Equality of Variances			
Method	Num DF	Den DF	F Value	Pr >F
Folded F	15	15	1.77	0.2811

Table A-17. The GLM Procedure for extractable soil sodium (Na^{+}) amounts for samples collected from locations with ponderosa pines exhibiting symptoms of exposure to deicing salts, from up and downslope to the road, at 3, 20 and 60 feet from the road and at 0-6, 6-12 and 12-24 inches depths in the soil.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	6	44.3059	7.3843	47.80	<0.0001
Error	546	84.3480	0.1545		
Corrected Total	552	128.6540			

R-Square	Coeff Var	Root MSE	Na Mean
0.3444	84.4974	0.3930	0.4652

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Symptom	1	0.5978	0.5978	3.87	0.0497
Orientation	1	0.5816	0.5816	3.76	0.0529
Distance	2	41.5862	20.7931	134.60	<0.0001
Depth	2	1.5410	0.7702	4.99	0.0072

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Symptom	1	0.5369	0.5369	3.48	0..0628
Orientation	1	0.6639	0.6639	4.30	0.0386
Distance	2	41.6742	20.8371	134.88	<0.0001
Depth	2	1.5404	0.7702	4.99	0.0072

Table A-18. Extractable soil sodium (Na^+) amounts for samples collected at 20 feet from the edge of the road pavement between locations with asymptomatic ponderosa pines and locations with pines exhibiting symptoms of deicing salt exposure.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	1.0888	0.2722	2.84	0.0258
Error	178	17.0640	0.0958		
Corrected Total	182	18.1527			

R-Square	Coeff Var	Root MSE	Na Mean
0.0600	73.0166	0.3092	0.4240

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Symptom	1	0.6008	0.6180	6.45	0.0120
Orientation	1	0.2504	0.2504	2.61	0.1078
Depth	2	0.2203	0.1101	1.15	0.3193

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Symptom	1	0.6008	0.6008	6.27	0..0132
Orientation	1	0.2453	0.2453	2.56	0.1114
Depth	2	0.2203	0.1101	1.15	0.3193

Table A-19. Extractable soil sodium (Na^+) amounts for samples collected at 3 feet from the pavement edge. Least Square Means Adjusted for Multiple Comparisons: Tukey-Kramer.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	3.5470	0.8868	2.50	0.0441
Error	180	63.8104	0.3545		
Corrected Total	184	67.3574			

R-Square	Coeff Var	Root MSE	Na Mean
0.0527	72.7199	0.5954	0.8188

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Symptom	1	0.1410	0.1410	0.40	0.5291
Orientation	1	0.4763	0.4763	1.34	0.2479
Depth	2	2.9298	1.4649	4.13	0.0176

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Symptom	1	0.1614	0.1614	0.46	0..5007
Orientation	1	0.4774	0.4774	1.35	0.2474
Depth	2	2.9298	1.4648	4.13	0.0176

Depth	Na LS MEAN	LSMEAN
0-6 inches	0.64228	1
6-12 inches	0.8653	2
12-24 inches	0.9380	3

	Least Squares Means for effect Depth Pr>|t| for H0; LS Means (i)=LSMean(i) Dependent Variable: Na		
i/j	0-6 inches	6-12 inches	12-24 inches
0-6 inches		0.0923	0.0184
6-12 inches	0.0923		0.7787
12-24 inches	0.0184	0.7787	

Table A-20. Extractable soil sodium (Na^+) amounts for samples collected at 60 feet from the centerline of the road.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	0.0722	0.0180	2.15	0.0770
Error	180	1.5138	0.0084		
Corrected Total	184	1.5860			

R-Square	Coeff Var	Root MSE	Na Mean
0.0455	60.2462	0.0917	0.1522

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Symptom	1	0.0114	0.0114	1.35	0.2462
Orientation	1	0.0496	0.0496	5.90	0.0162
Depth	2	0.0112	0.0056	0.67	0.5142

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Symptom	1	0.0111	0.0111	1.32	0..2527
Orientation	1	0.0499	0.0499	5.93	0.0159
Depth	2	0.0112	0.0056	0.67	0.5142

Table A-21. The GLM procedure for soil pH for samples collected at a depth of 0-6 inches from all sites.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	7.1160	1.7790	13.03	<0.0001
Error	40	5.4632	0.1366		
Corrected Total	44	12.5792			

R-Square	Coeff Var	Root MSE	pH Mean
0.5657	5.0553	0.3696	7.3104

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Symptom	1	0.8474	0.8474	6.20	0.0170
Orientation	1	0.3237	0.3237	2.37	0.1315
Depth	2	5.9449	2.9724	21.76	<0.001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Symptom	1	0.6791	0.6791	4.97	0.0314
Orientation	1	0.3839	0.3839	2.81	0.1014
Depth	2	5.9449	2.9725	21.76	<0.001

Table A-22. The GLM procedure for soil sodium absorption ratio (SAR) for samples collected at a depth of 0-6 inches from all sites.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	32.1526	8.0382	3.08	0.0265
Error	40	104.3547	2.6088		
Corrected Total	44	136.5074			

R-Square	Coeff Var	Root MSE	SAR Mean
0.2355	100.0784	1.6152	1.6139

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Symptom	1	2.9117	2.9117	1.12	0.2971
Orientation	1	2.7255	2.7255	1.04	0.3129
Depth	2	26.5155	13.2577	5.08	0.0108

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Symptom	1	2.9846	2.9846	1.14	0.2912
Orientation	1	2.2530	2.2530	0.86	0.3583
Depth	2	26.5155	13.2577	5.08	0.0108

Table A-23. The GLM Procedure for extractable soil magnesium (Mg^{2+}) amounts for samples collected from locations with ponderosa pines exhibiting symptoms of exposure to deicing salts, from up and downslope to the road, at 3, 20 and 60 feet from the road and at 0-6, 6-12 and 12-24 inches soil depths.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	6	2.1321	0.3554	3.82	0.0010
Error	546	50.8574	0.0931		
Corrected Total	552	52.9896			

R-Square	Coeff Var	Root MSE	Mg Mean
0.0402	135.8478	0.3052	0.2247

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Symptom	1	0.5704	0.5704	6.12	0.0136
Orientation	1	0.0110	0.0109	0.12	0.7322
Distance	2	0.6160	0.3080	3.31	0.0374
Depth	2	0.9349	0.4674	5.02	0.0069

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Symptom	1	0.5916	0.5916	6.35	0..0120
Orientation	1	0.0120	0.0120	0.13	0.7198
Distance	2	0.6125	0.3062	3.29	0.0381
Depth	2	0.9349	0.4674	5.02	0.0069

Table A-24. Extractable soil magnesium (Mg^{2+}) amounts for samples collected at 20 feet from the edge of the pavement between locations with asymptomatic ponderosa pines and locations with pines exhibiting symptoms of deicing salt exposure.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	1.1772	0.2943	4.55	0.0016
Error	175	11.3157	0.0647		
Corrected Total	179	12.4929			

R-Square	Coeff Var	Root MSE	Mg Mean
0.0942	99.6724	0.2542	0.2551

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Symptom	1	0.7577	0.7577	11.72	0.0008
Orientation	1	0.0060	0.0060	0.09	0.7616
Depth	2	0.4135	0.2068	3.20	0.0433

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Symptom	1	0.7432	0.7432	11.49	0.0009
Orientation	1	0.0073	0.0073	0.11	0.7374
Depth	2	0.4135	0.2067	3.20	0.0433

Table A-25. Extractable soil magnesium (Mg^{2+}) amounts for samples collected at 20 feet from the edge of the pavement. Least Square Means Adjusted for Multiple Comparisons: Tukey-Kramer.

Depth	Mg LS MEAN	LSMEAN
0-6 inches	0.1882	1
6-12 inches	0.2371	2
12-24 inches	0.3051	3

	Least Squars Means for effect Depth Pr>|t| for H0; LS Means (i)=LSMean(i) Dependent Variable: Mg		
i/j	0-6 inches	6-12 inches	12-24 inches
0-6 inches		0.5446	0.0338
6-12 inches	0.5446		0.3103
12-24 inches	0.0338	0.3130	

Table A-26. The GLM Procedure for extractable soil chloride (Cl^-) amounts for samples collected from locations with ponderosa pines exhibiting symptoms of exposure to deicing salts, from up and downslope to the road, at 3, 20 and 60 feet from the road and at 0-6, 6-12 and 12-24 inches soil depths.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	6	4.6073	0.7679	3.91	0.0008
Error	547	107.4791	0.1965		
Corrected Total	553	112.0864			

R-Square	Coeff Var	Root MSE	Cl Mean
0.0411	256.1107	0.4433	0.1731

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Symptom	1	0.5150	0.5150	2.62	0.1060
Orientation	1	0.6378	0.6378	3.52	0.0721
Distance	2	2.3949	1.1975	6.09	0.0024
Depth	2	1.0596	0.5298	2.70	0.0684

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Symptom	1	0.4994	0.4994	2.54	0..1115
Orientation	1	0.6041	0.6041	3.07	0.0801
Distance	2	2.4013	1.2007	6.11	0.0024
Depth	2	1.0596	0.5298	42.70	0.0684

Table A-27. Extractable soil chloride (Cl^-) amounts for samples collected at three feet from the edge of the pavement. Least Square Means Adjusted for Multiple Comparisons: Tukey-Kramer.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	0.2324	0.0581	17.56	,0.0001
Error	183	0.6055	0.0033		
Corrected Total	187	0.8379			

R-Square	Coeff Var	Root MSE	Cl Mean
0.2774	65.7734	0.0575	0.0875

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Symptom	1	0.0021	0.0021	0.62	0.4304
Orientation	1	0.0225	0.0225	0.81	0.0098
Depth	2	0.2078	0.1039	31.40	<0.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Symptom	1	0.0015	0.0015	0.47	0..4949
Orientation	1	0.0218	0.0218	6.58	0.0111
Depth	2	0.2078	0.1039	31.40	<0.0001

Depth	Cl LS MEAN	LSMEAN
0-6 inches	0.2379	1
6-12 inches	0.1665	2
12-24 inches	0.2800	3

	Least Squares Means for effect Depth Pr>|t| for H0; LS Means (i)=LSMean(i) Dependent Variable: Na		
i/j	0-6 inches	6-12 inches	12-24 inches
0-6 inches		,0.0001	<0.0001
6-12 inches	<0.0001		0.0841
12-24 inches	<0.0001	0.0841	