A PRELIMINARY STUDY OF THE EFFECT OF CALCIUM CHLORIDE HIGHWAY ANTI-ICER LIQUID ON ROADSIDE TREES IN LEAVENWORTH, WASHINGTON

By

JASON LENNART DIRKSE

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To the faculty of Washington State University:

The members of the Committee appointed to examine the thesis of JASON LENNART DIRKSE find it satisfactory and recommend that it be accepted.

Chair

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Abstract

By Jason Lennart Dirkse
Washington State University
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Chair: Eldon Franz

Recently observed foliar injury of trees along roads in and around Leavenworth, Washington, has elicited concern as to the cause of the injury. Leaves of certain trees, most noticeably big-leaf maple (*Acer macrophullym*), become browned, dried, and curled in early summer. However, these symptoms are only seen along certain stretches of certain roads, most severely along a 7-mile portion of State Highway 2 west from Leavenworth, and along the first ~4 miles of Icicle Road near Leavenworth. While the symptoms look similar to those of drought conditions, drought cannot sufficiently explain the limited and specific geographic distribution of the observed symptoms. A survey of relevant scientific literature reveals that highway anti-icer liquids applied to prevent ice build-up can have a similar effect on roadside trees as that which is observed. This explanation would more adequately explain the observations, and upon further investigation, there are a number of compelling reasons to suspect anti-icers as the cause of the observed injury symptoms. This study investigates the effect of highway anti-icers (specifically calcium chloride) on trees when added to the soil in which the tree is growing. Tree saplings were grown in a greenhouse, divided into five treatment groups, each containing three individuals of four species—black cottonwood, Douglas fir (*Pseudotsuga menziesii*), big-leaf maple (*Acer macrophyllum*), and Ponderosa pine (*Pinus ponderosa*)—for a total of 12 trees per treatment group. Each treatment group was given a different concentration of anti-icer liquid diluted with deionized water, added to the soil, once weekly for eight weeks. Growth was monitored both during and at the conclusion of the experimental period to determine if different concentrations of anti-icer resulted in different growth rates among the treatment groups. It was found that the anti-icer treatments caused significant injury to the trees, producing leaf browning and die-back, and likely killed all trees except the control group. Further study of this topic is warranted, as this study provided reason to suspect that highway anti-icers can cause significant damage to trees growing in the soil to which the anti-icer is added.

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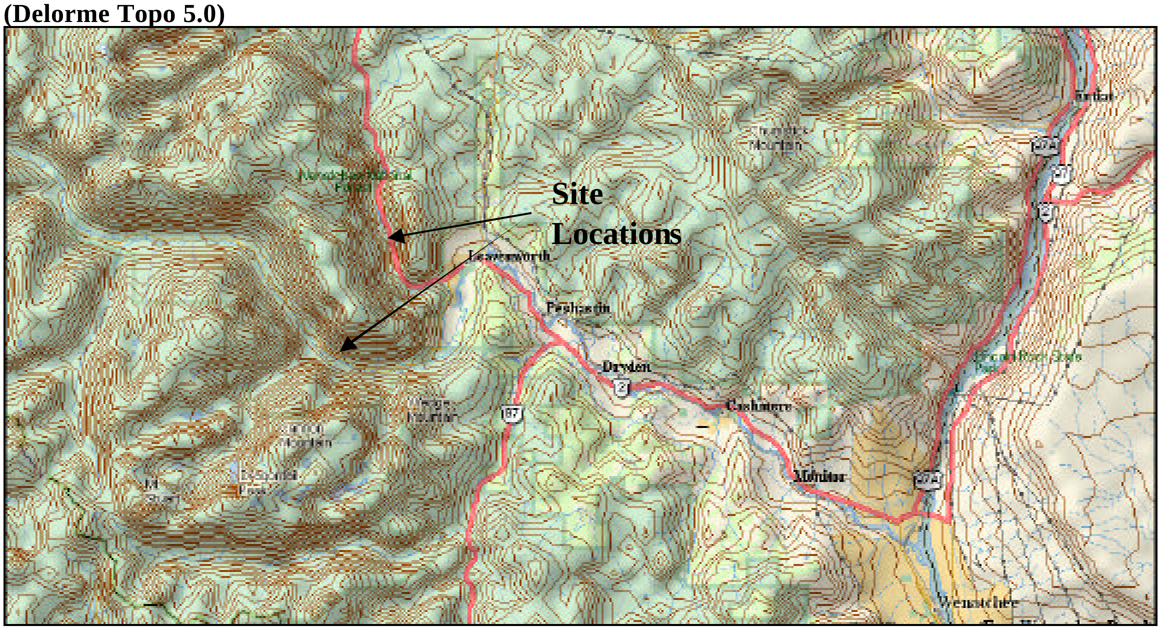
1 INTRODUCTION

In recent years, it has been observed that certain trees growing along roads in and around the city of Leavenworth, Washington, appear less than healthy. The leaves of these trees dry out and turn brown in early- to mid-summer. Leaf margins become browned, while the center of the leaf typically remains more or less green (Photograph 1). In severe cases, the entire leaf is brown. The symptoms are most obvious in deciduous trees. Big-leaf maple (*Acer macrophyllum*) is the most affected, but black cottonwood (*Populus trichocarpa*) and ocean spray (*Holodiscus discolor*), among others, also display symptoms. The symptoms observed immediately call to mind drought as a likely cause, due to the dry appearance of the leaves. However, it will be shown in this paper that a more thoroughly satisfying explanation of the observed symptoms is that the trees are being injured by highway anti-icing chemicals.

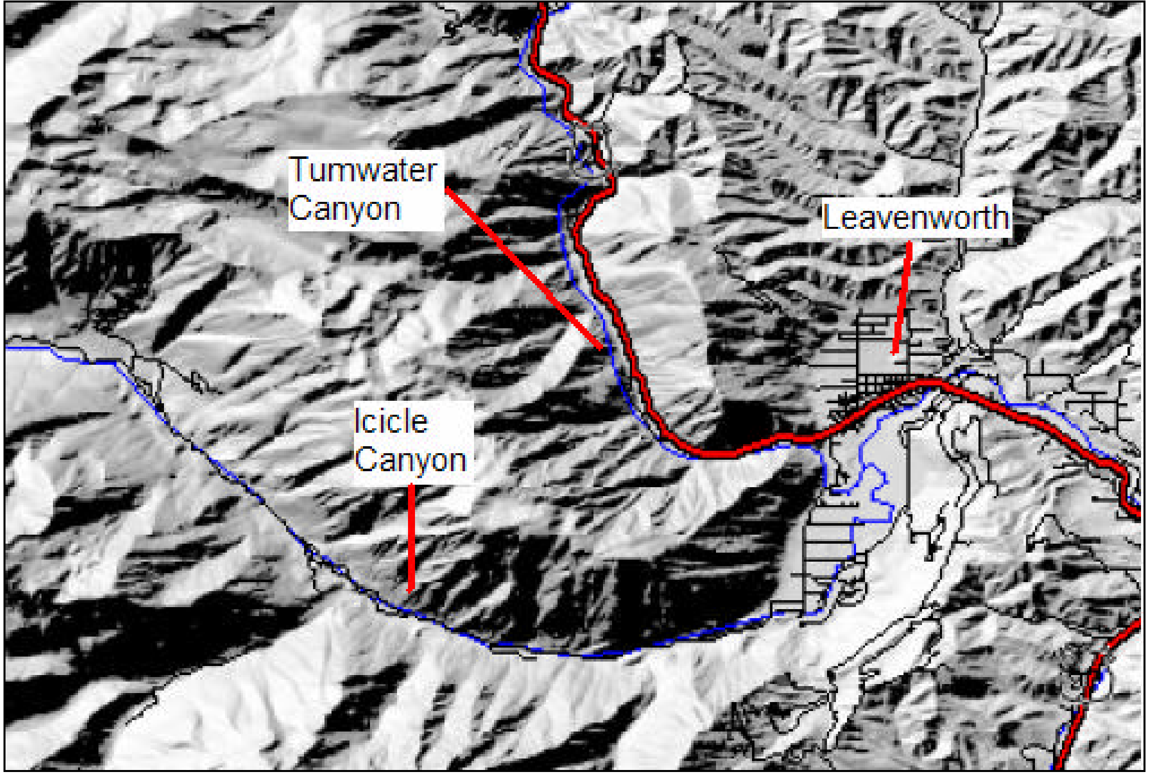
Photograph 1: Typical injury symptoms observed; notice the browned, curled leaf margins; 9-18-04

It is not just the peculiar symptoms that are worthy of note, but also the spatial distribution of the symptoms. Symptoms occur only on trees in particular stretches along certain roads. Along State Highway 2 in Tumwater Canyon, just west of Leavenworth, the road closely parallels the Wenatchee River (see Figures 1, 2). Throughout this 7-mile stretch of highway, big-leaf maple trees have prominently displayed browned leaves each of the past several summers. Yet immediately across the river, the same maple species shows no such symptoms. Maples along Icicle Road leading west from Leavenworth also display browned leaves every summer, but only for approximately the first four miles of Icicle Road, at the point where county road maintenance ends and a gate occasionally blocks winter automobile traffic. Beyond this gate, none of the previously mentioned symptoms have been observed among any tree, maple or otherwise.

Map 1: Vicinity map of Leavenworth, Tumwater Canyon/Wenatchee River, and Icicle Canyon/River (Delorme Topo 5.0)



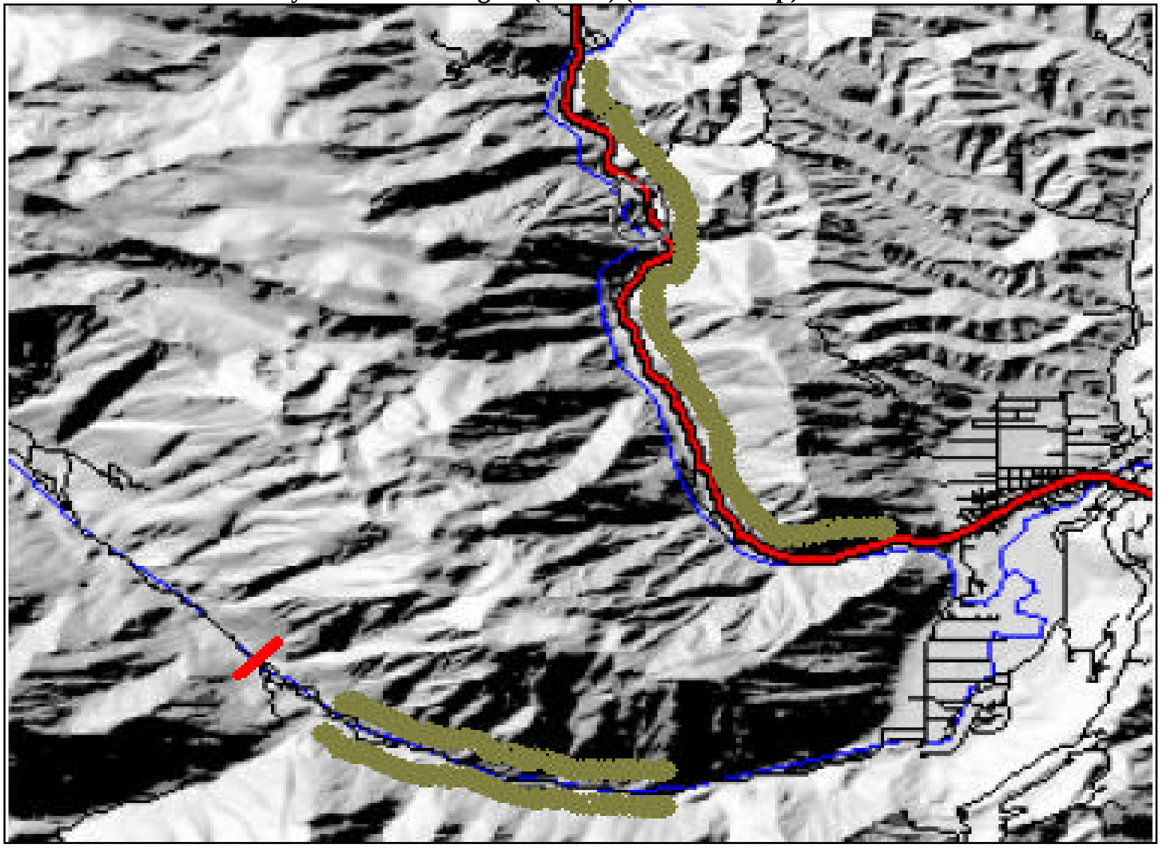
Map 2: Shaded relief map of Leavenworth, Tumwater Canyon/Wenatchee River, and Icicle Canyon/River (National Map)



Though the brown, dried leaf edges suggest drought, apparently healthy trees grow near obviously injured trees, as close as approximately 200 meters up the same road, or just across the river, with no apparently different ecological circumstances that would justify such a difference. It would seem that, if drought alone were the cause of the injury, that symptoms would appear more consistently, and would not only appear along roads. As it is, injury symptoms are only observed along certain stretches of certain roads.

Highway anti-icers as the cause would better explain the symptoms observed up Icicle Road. County road maintenance of Icicle Road ends at the Snow Lakes Trailhead, where there is a sign reading “End of County Road” (see Figure 3). This is the point where winter snowplow service and anti-icer application end. If anti-icers are indeed the cause, it would follow that injury symptoms would only be observed for the length of road to which anti-icers are applied.

Map 3: Icicle Road with main affected areas (in brown) and approximate location of Snow Lakes Trailhead/"End of County Maintenance" gate (in red) (National Map)



Photograph 2: "End of County Road" sign on Icicle Road; injury symptoms are observed no further

Photographs 3, 4: Contrast between injured maple trees that appear before the "End of County Road" sign (at left), and apparently health maple trees thereafter (at right); photographs taken on 9-18-04

This would also explain the symptoms along Hwy 2 in Tumwater Canyon only being observed along the road and not immediately across the river. It seems that drought would affect more trees than just those along roads. But highway anti-icer chemicals would only affect trees along roads. If anti-icer chemicals drain from the road when they turn the snow to water, they would enter the soil and, depending on the chemicals used for the anti-icer, could possibly affect the physiology of vegetation along the road.

Photograph 5: Bridge over the Wenatchee River; maple trees on the west side of the road (opposite side as the highway; at left in this picture) show none of the injury symptoms shown in maple trees on the east side along the highway

Photographs 6, 7: Contrast between injured maple trees that appear along Hwy 2 (at left), and apparently health maple trees immediately across the river (at right); photographs taken on 9-18-04

As mentioned above, these symptoms have been noticed only in recent years. No record exists that indicates when the symptoms first appeared, but local knowledge (including that of the author) indicates the injury symptoms appeared only within the past decade, implying that the causal agent is likely be something that has only been present in recent years. Local residents also recall the change in winter highway maintenance practices. Historically, sand was used to increase traction on snow-covered roads. However, in recent years, sand has been all but abandoned in favor of a liquid chemical anti-icer. A press release from November, 2003 by the Washington State Department of Transportation (WSDOT), corroborates with this observed change in highway maintenance:

> "The Washington State Department of Transportation initiated the chemical anti-icing program, statewide, four years ago. The WSDOT North Central Region (which includes Leavenworth) began testing the chemical anti-icers first, and this is its sixth winter utilizing chemical anti-icers." (WSDOT 2003)

If the "anti-icing program" was initiated between four and six years prior to 2003—between 1997 and 1999—this would approximately coincide with the timing of the first observation of the injury symptoms on the trees in question. This timeline also corresponds with the observed changes in highway maintenance.

Because of the circumstances described above, it is hypothesized that the observed foliar injury in Leavenworth, Washington, is a result of highway anti-icer chemicals applied to winter roads. The purpose of this paper is to review pertinent literature on the topic and to discuss research that has been conducted to test that hypothesis.

2 LITERATURE REVIEW

While anecdotal connections between observed leaf injury and highway anti-icers can be hypothesized, this is not enough to assign a causal relationship. To determine the state of scientific knowledge regarding anti-icers and any relation to vegetation injury, the existing body of scientific literature has been examined. As it turns out, in the words of Barrick, "reports of deicing salt damage in highway plantings are legion." (Barrick, p. 203, 1980) Deicing salts have been in use since the early 1900s, and their effect on roadside plant life has been documented since the 1940s. Following is a review of pertinent scientific literature.

2.1 About Anti- / De-icers

The WSDOT defines "anti-icing" as "the practice of applying chemicals to roadways to prevent frost and ice from forming or if it does, to keep it from compacting and bonding onto the highway (WSDOT 2003)." Anti-icing agents lower the freezing point of the water on roadways (in the form of snow, ice, or water), thus either reversing or preventing the process of ice accumulation on roadways that causes dangerous driving conditions. They are either applied before an ice or snow event to prevent accumulation, or after an event to melt accumulated ice and snow. Typically, liquid anti-icers (Calcium Magnesium Acetate [CMA], Calcium Chloride [$CaCl_2$]) are used before snow events as a preventative measure, and solid anti-icers (sand, rock salt) are used after snow events to melt the accumulation and improve traction (WSDOT 2003).

Historically, either rock salt (NaCl) or sand has been most commonly used to improve traction. For decades, NaCl has been applied in prodigious quantities to both North American and European roads. From 1965 through 1970, Great Britain applied an average of 1,052,400 tons of NaCl to roadways every year, West Germany applied 887,200 tons, and The Netherlands applied 269,400 (Dobson, 1991). Naturally, more severe winters require more NaCl. In especially severe winters, it has been reported that up to 5 kg of NaCl can be applied to each square meter of roadway (Dobson, 1991). This liberal application of NaCl has been documented as leading to corrosion of bridge structures, automobiles, and the road surface itself (Dobson, 1991).

Sand has also commonly been used to improve winter driving conditions. While lacking the ice-melting properties of salt, sand improves traction by increasing friction on the road surface. But sand requires frequent re-application, as it is easily blown to the shoulder by passing vehicles. Sand kicked up by passing cars has had a demonstrable effect on air quality, has been shown to increase turbidity in nearby surface water, and reduces the aesthetics of the roadside environment (WSDOT 2003).

Liquid anti-icers attempt to address the problems of corrosion, excessive environmental stress, and air and water quality degradation. Liquid anti-icers are able to remain on the road surface longer, are designed to be less corrosive to automobiles, and to minimize detrimental effects on the roadside environment. (WSDOT 2003)

2.2 Common Anti-Icers

While the first and still most common ice-melting agent used on highways is NaCl, other chemical anti-icers are being more widely-used lately: 1) Calcium Magnesium Acetate (CMA), the “least aggressive (weakest), but most environmentally benign;” 2) Magnesium Chloride, “stronger and used in most parts of the state on roads at higher elevations or those subject to colder temperatures;” and 3) Calcium Chloride ($CaCl_2$), “used when conditions can be most severe. It is effective to temperatures well below freezing where other anti-icers are not (WSDOT, 2003)." The North Central Region's highway maintenance supervisor, Dwayne Standerford, indicated that $CaCl_2$ is used in the region due to the severe winter conditions (pers. comm., 2004). $CaCl_2$ has more ice-melting ability than NaCl: "Whereas NaCl has deicing effect till about -8ºC, $CaCl_2$ can be used till about -20ºC" (Bogemans, Neirinckx, Stassart, p. 203, 1989). Rich notes that "calcium chloride is effective in ice removal, but is more expensive and more difficult to store and handle than sodium chloride." (Rich, p. 78a)

This literature review will only address anti-icers that are relevant to the present research question: NaCl and $CaCl_2$.

2.2.1 NaCl

NaCl has been the subject of the most studies of any anti-icer chemical. The damage done by NaCl has been well documented: "There is no doubt that salinity adversely affects the growth of plants (Strogonov, p. 45, 1964)." Symptoms similar to those observed around Leavenworth are frequently described in trees affected by NaCl. Buschbom indicates that NaCl used to melt ice on German highways results in "negative effects on the lively environment. Most noticeable is the injury to roadside trees and shrubs (Buschbom, 350, 1980)." Symptoms are often described in similar terms: "burning or browning," "chlorosis," (Bryson, Barker, pp. 67, 69, 2002; Günter, Wilke, p. 211, 1983), "leaf burn," "limb die-back," (Button, Peaslee, p. 121, 1970; Guttay, p. 952, 1976), "necroses at the edges of leaves," "dead branches," (Günter, Wilke, p. 211, 1983), "marginal leaf scorch," "early autumn leaf coloration and defoliation," "reduced shoot growth," (Guttay, p. 952, 1976), "brown" or "necrotic tissue," (Hall *et al.*, p. 245, 1972), "severe leaf scorch," (Holmes, Baker, p. 633, 1966), "browning or burning of the foliage," leaf tip burning," (Kliejunas, p. 3, 1989), "premature foliar coloration," "marginal leaf scorch," "defoliation," (Lacasse, Rich, p. 1071, 1964), etc.

A US Forest Service study of conifer damage and mortality in the Lake Tahoe area determined the cause to be "excessive levels of sodium and chloride as the cause" of the "foliar injury (Kliejunas, 1989)." Kliejunas also noted more severe injury on sides of the affected trees that faced the road. Buschbom reports "negative effects of chloride on the lively environment" along highways in Germany as a result of NaCl use as a deicing salt (Buschbom, 1980).

Rich found that the appearance of leaf damage symptoms was not dependent on the age or size of the tree: "The correlation between symptoms and dbh was not significant…(77a)" Bicknell and Smith found that certain tree seeds germinated at a lower rate when in soil that received NaCl treatments at concentrations similar to those found in roadside soil due to NaCl deicers (Bicknell and Smith, 1975).

2.2.2 $CaCl_2$

While fewer studies have been done on $CaCl_2$ than on NaCl, these studies document $CaCl_2$ causing vegetation damage similar to that caused by NaCl.

Paul *et al.* conducted studies into the effect of $CaCl_2$ on certain deciduous roadside tree species and found that $CaCl_2$ causes "foliar necrosis", though species differ in their sensitivity to $CaCl_2$ (Paul *et al*, p. 277, 1987). Strong observes that, since 1930, many cases of "injury"—also described as "leaf scorch"—to trees along roads treated with calcium chloride as a "dust palliative" have been recorded (Strong, 1944). In the 1920s, $CaCl_2$ was used extensively to reduce dust on gravel roads. "The chemical was first used by spreading heavy applications on the road surface, and it was during this period that considerable injury to roadside vegetation was observed and public criticism consequently aroused (210)." Strong notes that $CaCl_2$ was responsible for many of the reported cases of leaf scorch, but not all (209).

2.3 Relationship Between Foliar Injury and Elevated Soil Salt Concentrations

Many studies have found a relationship between visible leaf injury and abnormally high concentrations of sodium or chloride in soil or leaf tissue. Button found that trees along the side of a road that directly received highway drainage had less vigor, more leaf burn, more limb dieback, and significantly higher chloride content (percent leaf dry matter) than trees on the side of the road with a highway drainage system that diverted road runoff away from the trees (Button, 1964). Buschbom found that, while elevated soil salt levels do coincide with leaf damage, there does not appear to be a reliable linear relationship between soil salt levels and the degree of damage to the tree (Buschbom, 1980). Guttay, however, found that "progressively greater dieback was significantly correlated with…increased Na and chloride in roots and in the soil of the rhizosphere (Guttay, p. 952, 1976)." Hofstra and Hall found that, in trees grown in controlled temperature chambers, "the amount of injury that developed after 3 weeks at 15° C appeared to be directly related to the concentration of sodium and chloride in the leaf tissue (p. 244)." Other studies (Holmes, Baker 1966; Kliejunas *et al.* 1989; Lacasse, Rich 1964; Monk, Wiebe 1961; etc.) document similar conclusions of foliar injury coinciding with elevated sodium and/or chloride concentrations in soil or leaves.

2.4 Two Vectors of Injury

Two vectors of salt injury in plants have been noted: direct spray of road melt, and soil/root uptake. It has been noted that salt spray injury is more commonly observed in conifer trees, while soil uptake injury is more common in deciduous trees.

2.4.1 Salt Spray Injury (Coniferous Trees)

Coniferous trees have been observed to display severe symptoms and seem to be affected most by deicer salts. Kliejunas *et al.* conducted their study in response to widespread conifer damage mortality in the Lake Tahoe region. They concluded that roadside conifers were damaged by highway salts, and since greater damage was observed on sides of trees facing the road, conifers suffer salt injury by receiving direct spray of highway ice and snow that has been melted by NaCl and turned to salt water. This type of damage is commonly associated with conifers because, unlike deciduous trees, they retain their foliage during the winter and thus have more foliar surface area by which to receive salt spray (Bryson and Barker, 2002).

2.4.2 Soil Salt Uptake (Deciduous Trees)

Soil uptake injury symptoms are typically more dispersed throughout the tree (rather than being more severe on the side of the tree facing the road), and manifest in spring and summer when deciduous trees begin leafing (Button 1964). Both vectors of salt injury manifest similar symptoms.

In Guttay's study, entitled, "Impact of Deicing Salts Upon the Endomycorrhizae of Roadside Sugar Maples," (Guttay, 1976) the same symptoms observed in big-leaf maple trees in Leavenworth are described in sugar maples in Connecticut. Guttay makes a connection between the symptoms and deicing treatments: "Unusual levels of Na (sodium) and chloride in plant tissues combined with the symptoms of marginal leaf scorch, early autumn leaf coloration and defoliation, reduced shoot growth, and branch dieback suggest a cause and effect relationship (952)." Guttay concludes that "salt damage on sugar maple is attributed to a progressive root destruction as annual salt applications continue and an increasing top dieback as the diminishing root system is unable to sustain the top (952)." Holmes also identifies NaCl as causing leaf scorch in roadside sugar maples, reasoning from the coincidence of injury symptoms and high foliar chloride: "trees with little or no foliar injury had low foliar chloride levels (0.05-0.6% of dry weight), whereas those with severe leaf scorch had high foliar chloride levels (about 1%) (Holmes, 1966)."

2.5 Tree Species Documented with Salt Injury

Salt injury symptoms have been reported in a number of tree species, including:

- ***Abies*** (fir) (Kliejunas *et al.* 1989; von Sury, Flückiger 1989)
- ***Acer*** (maple) (Button 1964; Holmes, Baker 1966; Horsley *et al.* 2002; Hutchinson, Olson 1967; Lacasse, Rich 1964; Shortle, Kothemier, Rich 1972; Paul, Rocher, Impens 1987)
- ***Kalmia*** (mountain laurel) (Bryson, Barker 2002)
- ***Picea*** (spruce) (Bryson, Barker 2002; Bogemans, Neirinckx, Stassart 1989)
- ***Pinus*** (pine) (Bryson, Barker 2002; Hofstra, Hall; Kliejunas *et al.* 1989; Sands, Clarke 1977; Foster, Sands 1977)
- ***Platanus*** (sycamore) (Paul, Rocher, Impens 1987)
- ***Pseudotsuga*** (Douglas fir) (Kliejunas *et al.*1989)
- ***Rhus*** (sumac) (Bryson, Barker 2002)

- ***Sorbus*** (mountain ash) (Paul, Rocher, Impens 1987)
- ***Thuja*** (cedar) (Hofstra, Hall; Kliejunas *et al.*)
- ***Tilia*** (linden) (Paul, Rocher, Impens 1987)

2.6 Drought

Drought conditions can induce similar-looking symptoms in trees. "Since the symptoms were no different from leaf scorch caused by drought, it was impossible to determine how much injury was due to each factor." (Lacasse, Rich, p. 1071) Sucoff notes that drought conditions and soil salts result in greater injury than either factor does separately (1975).

2.7 Calcium and Chlorine in Plants

Both calcium and chlorine are "essential elements"—those a plant requires in order to complete its growth and development. Essential elements are divided into two general categories—macronutrients and micronutrients. Macronutrients are those needed in relatively high concentrations (typically in excess of about 10 mmole kg^{-1} of dry weight), and micronutrients are those needed in far lower concentrations (typically less than 3 mmole kg^{-1} of dry weight) (Hopkins, 1995). While both calcium and chlorine are essential elements, both can be toxic to plants if present in excess.

2.7.1 Calcium

According to Hopkins, calcium is a macronutrient, required at 125 mmole/kg^{-1} of dry weight in higher plants. Calcium is typically found in the form of an ion, meaning that a single calcium atom exists by itself and possesses an electrical charge—positive in the case of calcium, making calcium a "cation". In fact, calcium ions bear a double positive charge—Ca^{++}.

Calcium is critical to plants due to its role in cell division. It is crucial in the formation of a mitotic spindle during cell division of higher plants, and also contributes to the formation of a cell plate that forms between the newly divided cells. Calcium is also known to contribute to the physical integrity and functionality of membranes (Hopkins, 1995).

2.7.2 Chlorine

Chlorine is classified as a micronutrient and is required in far lower concentrations than calcium. The element chlorine is most commonly found in nature in the form of an ion—chloride (Cl^-)—making chloride an “anion”. Chloride is primarily used by higher plants in oxygen-evolving reactions as a part of photosynthesis. It is a major counterion and acts to maintain electrical neutrality across intracellular membranes. Chloride is also one of the major osmotically active solutes in cellular vacuoles, facilitating water transfer across cellular membranes (Hopkins, 1995).

2.8 Toxicity Levels

It has been noted that “leaf chloride concentration is a better indicator of the salt status of the plant, relative to damage rating, than is the leaf sodium concentration (Scharpf and Srago, 1974, p.5, 1989).” There is record of chloride toxicity in plants, with injury symptoms similar to those observed in Leavenworth. Chloride toxicity in lychee trees in Australia is noted, and symptoms described as “lack of vigor, leaf drop, signs of desiccation or burning on the leaf margins, fruit drop, and failure to develop fruit.” (“Chloride toxicity in Lychee,” 2005) Harper noted that visible injury to pecan trees occurs when chloride content is less than 0.6% of dry weight of leaf (1946). For these reasons, leaf and soil chloride level will be the focus of this study.

2.9 How Damage Occurs

Paul *et al.* propose three hypotheses to explain highway salt phytotoxicity: 1) chloride could accumulate in the leaves and reach a phytotoxic level, 2) high concentrations of chloride in soils could modify mineral nutrition, and 3) water absorption via the roots could be disturbed, on account of an increase in osmotic pressure of the soil solution. (277)

Sucoff, in his study on highway anti-icers in Minnesota, concludes that his study "either confirmed or newly established that salt is responsible for damage to woody plants growing along many Minnesota Roads." He offers a number of explanations as to why anti-icers cause injury:

After entering soil:

- NaCl added to soil decreases the availability of soil water, which decreases the plant's ability to take up water, reducing growth (p. 13)
- NaCl may also decrease the availability of other ions—like calcium—to the roots, decreasing root growth, which leads to more water deficits in the tree (p. 13)
- elevated sodium levels in the soil breaks down soil aggregates or prevents their formation, leading to or maintaining soil compaction (p. 13)
- sodium raises soil pH above optimum level for ion uptake and root growth (p. 13)
- sodium can accelerate leaching of organic matter from soil (p. 13)

After entering plant:

- In high enough concentrations, Na^+ and Cl^- are toxic to plant cells—ions adversely affect cell membrane stability, leading to reduced growth and leaf death by bleaching of the chlorophyll (p. 13)

- NaCl has been found to decrease the cold resistance of hardwood twigs and potentially interact with low winter temperatures to produce twig dieback (p. 13)

Sucoff observed symptoms commonly noted with anti-icer injury: reduction of growth, marginal necrosis, premature fall coloration, premature leaf drop, leaves small and yellowing, leaves fewer in number, twig dieback, followed by dieback of entire branch systems, and finally tree death (p. 13)

2.10 Conclusion

As has been demonstrated, the existing body of scientific literature overwhelmingly supports the possibility of highway anti-icers causing damage to roadside vegetation. Both NaCl and $CaCl_2$ applied to roads have led to injury symptoms similar to those seen around Leavenworth.

3 MATERIALS AND METHODS

3.1 Field Samples

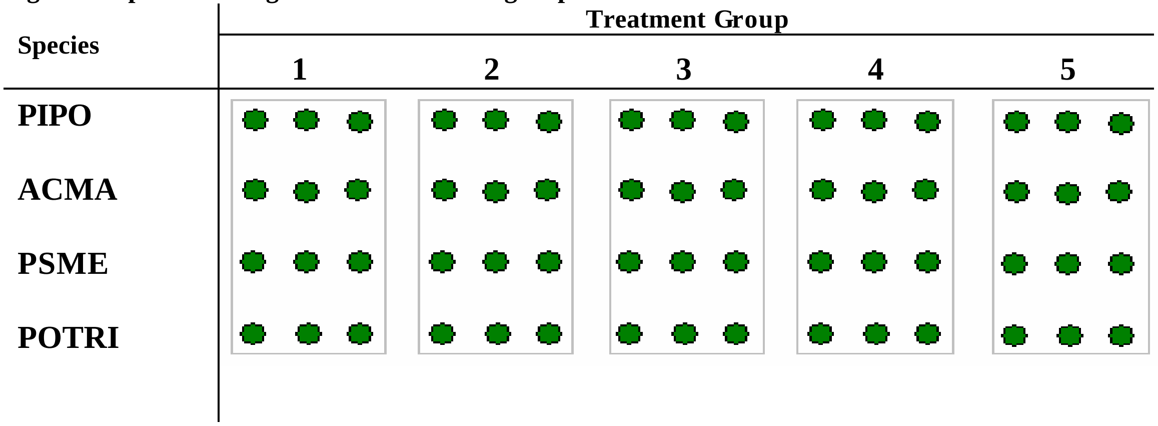
Many of the studies of foliar salt injury reviewed above noted unusually high levels of chloride in injured leaves and accompanying soil. If observed injury symptoms are indeed a result of anti-icer damage, then leaves displaying those symptoms and the soil in which affected trees were growing should have chloride levels significantly higher than those not showing such symptoms. To test this, both obviously injured and obviously uninjured leaves were collected from both Tumwater Canyon and Icicle Canyon. Soil samples were taken from underneath affected trees along sections of road to which anti-icer was known to be applied, and also from underneath unaffected trees in areas where anti-icers are known to not be applied. Samples were prepared in accordance with University of Idaho standard methods for preparation (Case, 2002) and tested by ion chromatography for chloride content.

3.2 Greenhouse Experiment

A greenhouse experiment was conducted from February 18 through April 15. Four tree species common around Leavenworth—Douglas fir (*Pseudotsuga menziesii* - PSME), Ponderosa pine (*Pinus ponderosa* - PIPO), Big-leaf maple (*Acer macrophyllum* – ACMA), and Black cottonwood (*Populous trichocarpa* - POTRI)—were selected for the experiment. Fifteen seedlings of each species were purchased from a native nursery near Leavenworth, potted with common potting soil in 1-gallon pots, and placed in a greenhouse.

The seedlings were divided into five treatment groups, each consisting of three individuals of each of the four species, for a total of 12 individual trees in each group, and a total of 60 trees. To avoid unequal growth due to edge effects, treatment groups and species were rotated weekly.

Figure 1: Spatial arrangement of treatment groups.



The trees were given artificial light and elevated temperatures to accelerate growth. A 300 mL treatment of a common $CaCl_2$ anti-icer was applied to the soil of each tree once weekly. Each of the five treatment groups was given a different concentration of $CaCl_2$ diluted with deionized water (Table 1). Additionally, all trees were watered once weekly with 300 mL of deionized water. Treatments were applied for a period of 8 weeks.

Table 1: Treatment groups and $CaCl_2$: deionized water ratio

Group	$CaCl_2$: Deionized Water Of Treatment	mL $CaCl_2$ Per Treatment	mL Water Per Treatment
1	100 : 0	300	0
2	50 : 50	150	150
3	25 : 75	75	225
4	12.5 : 87.5	37.5	262.5
5	0 : 100	0	300

3.2.1 Visual Observations

Photographs of the trees growing in the greenhouse experiment were taken weekly to visually document the condition of the trees. The intent was to compare visual symptoms to those observed in the field (leaf browning, early dieback, retarded growth, etc.). It is hypothesized that greenhouse-grown trees receiving $CaCl_2$ treatments (i.e. all but the control group—Group 5) will display injury symptoms before the experiment period is ended, though treatment groups receiving lower concentrations of $CaCl_2$ will display less severe symptoms.

3.2.2 Soil and Root Tissue Chloride Content

As mentioned above, many studies noted injury symptoms coinciding with high soil and plant tissue chloride levels. To test this, at the end of the experimental growing period soil and root samples were prepared from both the greenhouse trees and the field-collected soil and leaf samples. Samples were analyzed by ion chromatography to determine chloride content. (Originally, it was intended that leaf tissue be sampled for chloride; however, many greenhouse trees receiving $CaCl_2$ treatment failed to produce leaves, so roots were used instead. Because of this, greenhouse samples and field samples could not be directly compared for chloride concentration.) Samples were prepared using the method mentioned above. It was thought that samples taken from the field and samples taken from greenhouse trees that were given comparable anti-icer concentration treatments would have similar chloride levels (highway $CaCl_2$ is typically applied at 30% $CaCl_2$, 70% water—Standerford pers. comm., 2004).

Chloride content was compared across different treatment groups, and tree injury was visually documented and compared against chloride content. It was hypothesized that chloride levels will be highest in Group 1 and decrease with each treatment group as $CaCl_2$ concentration decreases, with Group 4 having the lowest chloride content, and Group 5 having normal chloride levels. It was also hypothesized that an inverse relationship will exist between root/soil chloride content and tree mass, due to expected reduction of growth of trees receiving higher chloride treatments.

3.2.3 Tree Height Increase

During the experiment period individual tree heights were recorded weekly to monitor growth. It was hypothesized that the less chloride a tree receives, the taller it would grow. It was also hypothesized that tree height increase and root chloride concentration would be inversely correlated—trees with more chloride will not grow as much. Height was measured in centimeters from the top of the edge of the pot to the top of the tree stem. Leaves extending above the top of the tree stem were generally not included in the height measurements.

3.2.4 Tree Weight Measurements

Upon completion of the experiment period, trees were weighed—leaves, stems, and roots separately, then combined for a total individual tree weight—and compared to examine differences in growth between different treatment groups. Trees were measured in grams. It was hypothesized that trees receiving higher concentrations of $CaCl_2$ treatment would have less mass according to the strength of the concentration—trees in the control group would be most massive, and masses would decrease as $CaCl_2$ concentration of treatment increased.

3.2.5 Leaf Surface Area

Upon completion of the experiment period, total leaf surface area of each tree was calculated using a leaf area meter (Photograph X). Surface area was measured in square centimeters. It was hypothesized that leaf surface area would exhibit an inverse relationship with concentration of $CaCl_2$ in treatment given to the tree—the control group would have the highest average leaf surface area, and area would decrease as $CaCl_2$ treatment concentration increased.

Photograph 8: Leaf area meter, calculating surface area of tree leaves

4 RESULTS

Since the greenhouse experiments represented a relatively small sample size—essentially 20 groups of three—no statistical analyses were conducted on the data. Initial height measurements were recorded for each individual tree prior to the experimental period. Final height was plotted against this initial height for each tree, as described in Section 4.3. Final mass and final leaf surface area have been plotted against total height increase, as described in Sections 4.4 and 4.5.

4.1 Visual Observations

As the photographs in Appendix 1 show, trees receiving anti-icer treatments displayed severe injury symptoms, such as browned, curled leaves and withered stems. Many trees failed to produce any leaves at all. Ponderosa pines in Groups 1-4 had browned needles one week into the experimental period (Appendix 1: Photograph 5). By the following week, Douglas firs began to show browned needles (Appendix 1: Photograph 9), and soon thereafter cottonwood leaves began turning brown as well (Appendix 1: Photograph 12). These symptoms are similar to symptoms observed in the field and symptoms described in the literature, though symptoms observed here were generally more severe than those observed in the field. See Appendix 1 for all the photographs.

4.2 Soil and Plant Tissue Chloride Content

4.2.1 Root Tissue—Greenhouse Experiment

Ion chromatographic analysis of root samples revealed significantly different levels of chloride among the five treatment groups. In all four species, chloride levels in the root samples—measured in parts per million—decreased as the concentration of deicer in the treatment decreased, as was expected.

Root samples of all four species in the group receiving 100% $CaCl_2$ showed levels above 1,000 ppm (see Table 2): cottonwoods averaged 1,289.19 ppm chloride, Douglas fir averaged 1,081.33 ppm, maple averaged 1,193.79, and Ponderosa pine averaged 1,098.29. Root samples receiving only deionized water averaged 7.11 ppm (cottonwood), 18.12 ppm (Douglas fir), 3.65 ppm (maple) and 16.68 ppm (Ponderosa pine). These data indicate that trees growing in soil to which deicer has been applied have significantly elevated chloride levels, and that chloride levels within plant tissue increase with the increased concentration of deicer applied. These results are consistent with the literature in that trees displaying injury symptoms have elevated root chloride levels (Guttay, 1976; Button, 1964). This also supports the hypothesis.

Table 2: Chloride content of root samples, average of three individuals of each species in each treatment group

Treatment Group	Average Root Chloride Concentration (ppm)			
	Cottonwood	Douglas Fir	Big-Leaf Maple	Ponderosa Pine
Group 1	1289.19	1081.33	1193.79	1098.29
Group 2	1124.79	890.45	804.15	866.78
Group 3	812.86	675.36	609.87	703.04
Group 4	460.76	350.20	585.72	431.32
Group 5	7.11	18.12	3.65	16.68

4.2.2 Leaf Tissue—Field Experiment

Field leaf samples taken from both trees displaying injury symptoms and trees appearing healthy were also measured for chloride concentration (see Table 3). Leaves that visually appeared healthy had chloride levels between 2 and 8 ppm. Leaves that showed injury symptoms had much higher chloride levels—between 40 and 167 ppm. This is consistent with the literature and supports the hypothesis, although the small sample size makes it difficult to draw any conclusions from the results.

Table 3: Leaf chloride content of field samples taken from injured trees and uninjured trees

Sample	Soil Chloride Concentration (ppm)	
	Injured	Uninjured
Tumwater 1	**168.33**	**2.56**
Tumwater 2	**166.86**	**2.96**
Icicle 1	**41.10**	**7.34**
Icicle 2	**40.36**	**7.10**

4.2.3 Soil Samples—Greenhouse Experiment

Ion chromatograph analysis of chloride content of the soil in which the trees discussed above were growing revealed a similar pattern of chloride concentration—soil to which a solution with higher $CaCl_2$ concentration was applied displayed higher levels of chloride. Trees from Group 1 were recorded to have foliar chloride levels in excess of 100,000 ppm, while trees from Group 5 were recorded with chloride levels between 10.56 ppm (m14) and 76.33 ppm (p14). Soil chloride levels ranged reasonably linearly from Group 1 to Group 5—decreasing with decreasing $CaCl_2$ treatment concentration. These results support the hypothesis.

Table 4: Chloride content of soil samples, average of three individuals of each species in each treatment group

Treatment Group	Average Soil Chloride Concentration (ppm)			
	Cottonwood	Douglas Fir	Big-Leaf Maple	Ponderosa Pine
Group 1	**102984.28**	**108500.98**	**125322.31**	**116815.06**
Group 2	**52598.61**	**51273.08**	**66335.48**	**52228.89**
Group 3	**32219.68**	**31154.78**	**33844.32**	**29557.13**
Group 4	**18866.75**	**14951.52**	**19367.75**	**17137.00**
Group 5	**43.53**	**41.56**	**21.25**	**62.55**

Clearly, the range of values observed in the root data and the range of values observed in the soil data are quite different: soil chloride concentration is much higher than root chloride concentration. This could be explained by different methods used to prepare samples, or by the fact that soil and trees were planted and contained in gallon pots for the duration of the experiment. In the field, anti-icer salts would have more chance to drain out of the soil or be diluted than they would in small pots. While these values may not accurately reflect the levels of deicer present in roadside soil, they do indicate that higher concentrations of deicer applications result in higher soil chloride levels.

4.2.4 Soil Samples—Field Experiment

Soil samples taken from along roads in the affected areas (Icicle and Tumwater Canyons) were also analyzed for chloride concentration. Results show little difference between affected and unaffected areas. Soils from unaffected sites in the Tumwater Canyon had values of chloride between 30 and 36 ppm; unaffected soils in the Icicle Canyon had between 36 and 91 ppm chloride. Soils from affected sites along Tumwater Canyon had between 22 and 58 ppm chloride; soils from affected sites in Icicle Canyon had between 43 and 75 ppm chloride. These results do not support the hypothesis, as it was expected that soils in which are growing trees showing injury symptoms would have much higher chloride levels than those from apparently unaffected areas. However, this could be partially explained by the fact that soils sampled from along roadways were sandy/gravelly soils, such that would drain quickly and would not likely hold anti-icer residue for long. Additionally, soil samples were taken to a depth of 12 inches. It is possible that the ions leach further down from the soil surface than 12 inches. Finally, such a small sample size makes it difficult to draw any conclusions from the results. Due to the variability of results, a true test of the hypothesis would need to be based on an more thorough sampling design to determine the scale and pattern of soil concentrations in the field.

Table 5: Soil chloride content of field soil samples taken from under uninjured trees and under injured trees (Sample "Tumwater Uninjured 3" and "Icicle Uninjured 2" were lost)

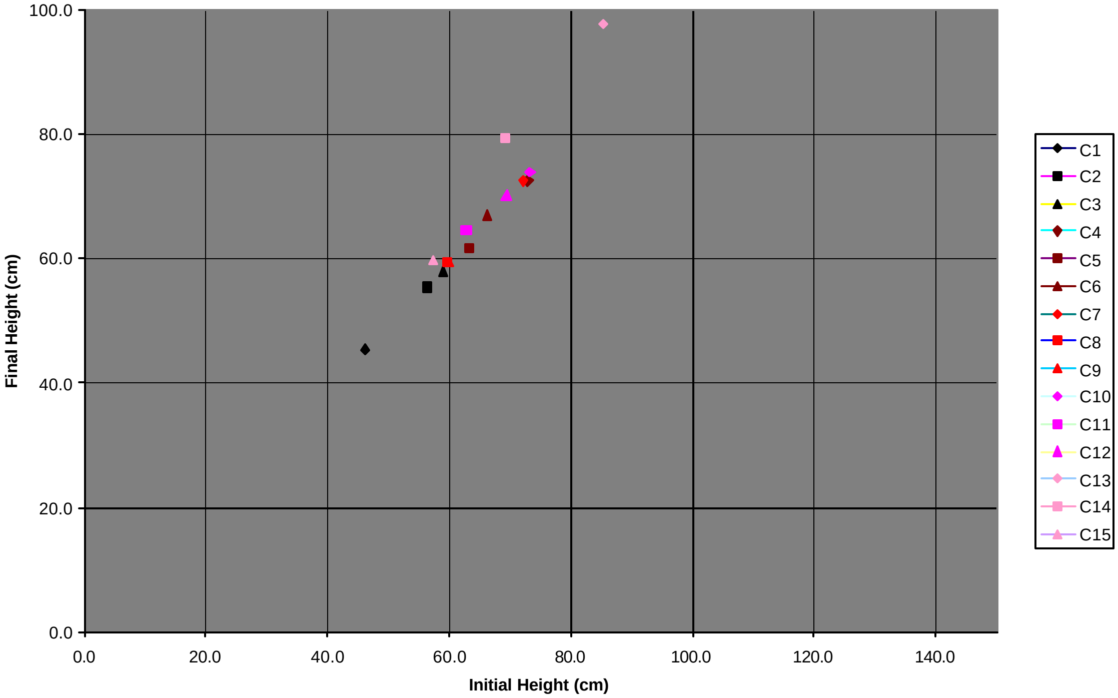
Sample	Soil Chloride Concentration (ppm)	
	Injured	Uninjured
Tumwater 1	44.92	30.67
Tumwater 2	22.83	35.90
Tumwater 3	57.08	
Icicle 1	53.76	36.13
Icicle 2	74.74	
Icicle 3	43.77	90.22

4.3 Tree Height Increase

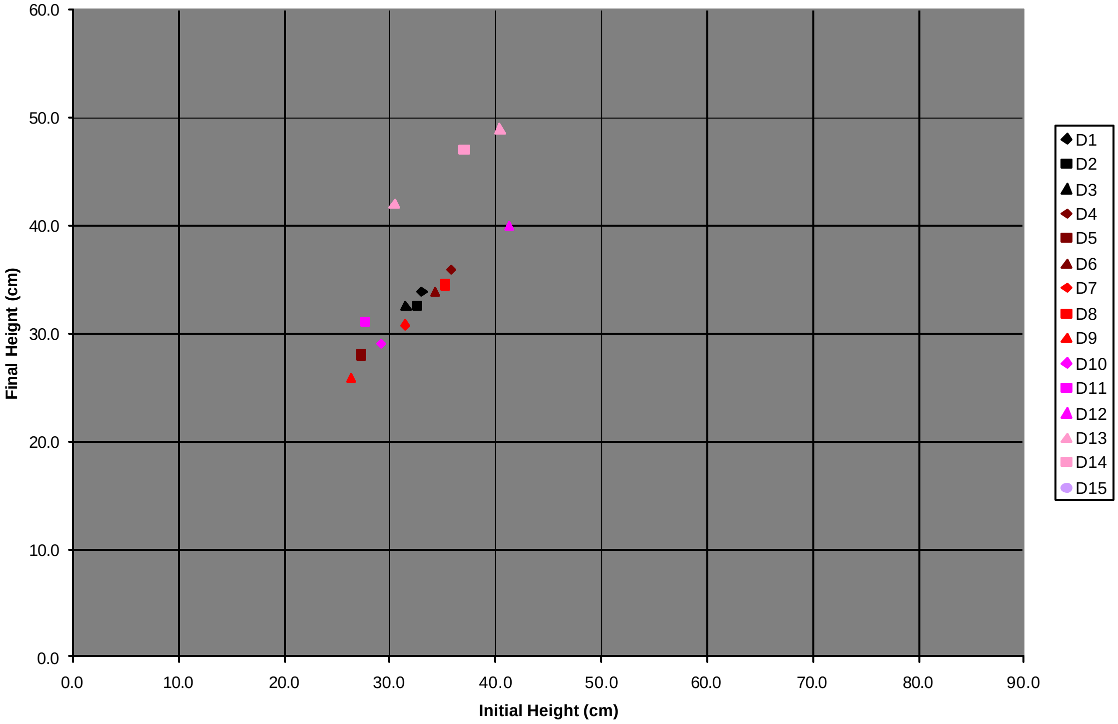
As hypothesized, trees in Group 5 exhibited the most growth over the eight-week period, typically around 10 centimeters. Also as hypothesized, growth in Groups 1-4 was significantly less (Graph 1). All treatment groups that received anti-icer exhibited little growth. In fact, many appear to have shrunk. Contrary to what was hypothesized, there was not a linear pattern of decreasing growth with increasing anti-icer concentration. Rather, it appears that all trees given anti-icer treatment were killed, and thus exhibited no real growth.

Graphs 1-4 plot initial tree height versus final tree height. All individuals, except those in Group 5, are tightly clustered along a diagonal line, indicating little or no change in height between the initial measurement and the final measurement. Group 5 trees are typically above this diagonal line pattern, showing that their final height was greater than their initial height. These graphs show that, basically, any tree receiving anti-icer treatment virtually did not grow or grew very little, so as to make it seem likely that they died soon after treatments started. Thus, differences of growth rates between Groups 1-4 will not be discussed; rather, only differences of growth between trees receiving anti-icer treatment (Groups 1-4) and trees not receiving anti-icer treatment (Group 5) will be discussed.

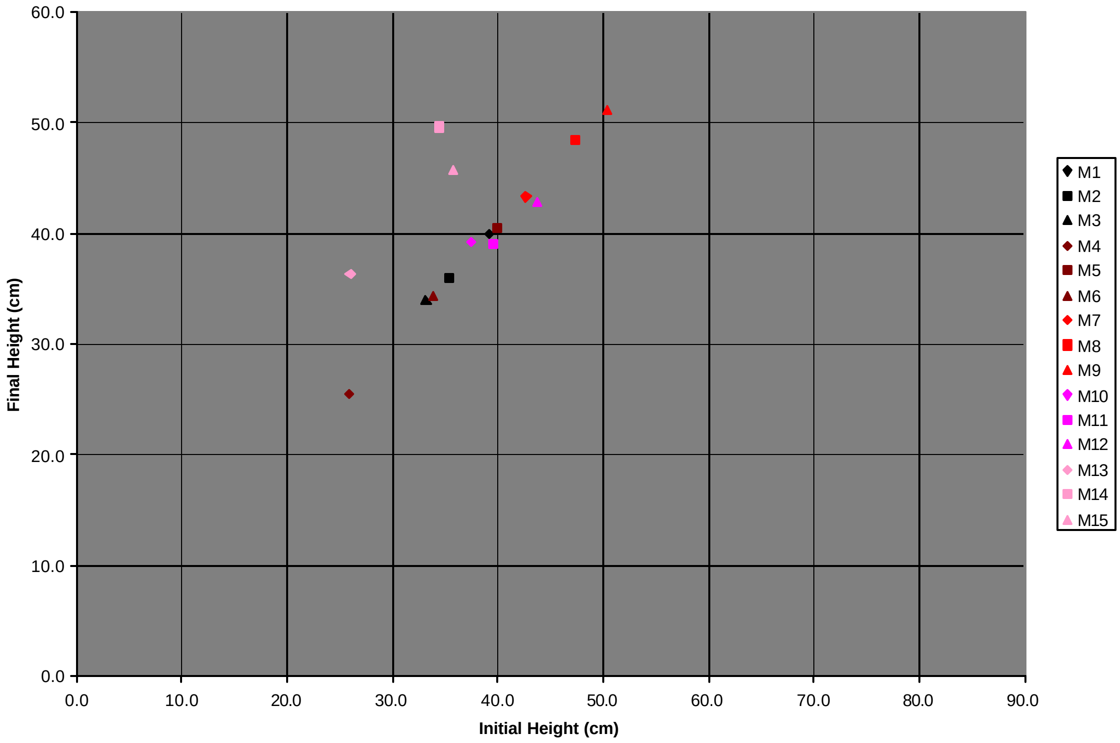
Graph 1: Cottonwood final height vs. initial height



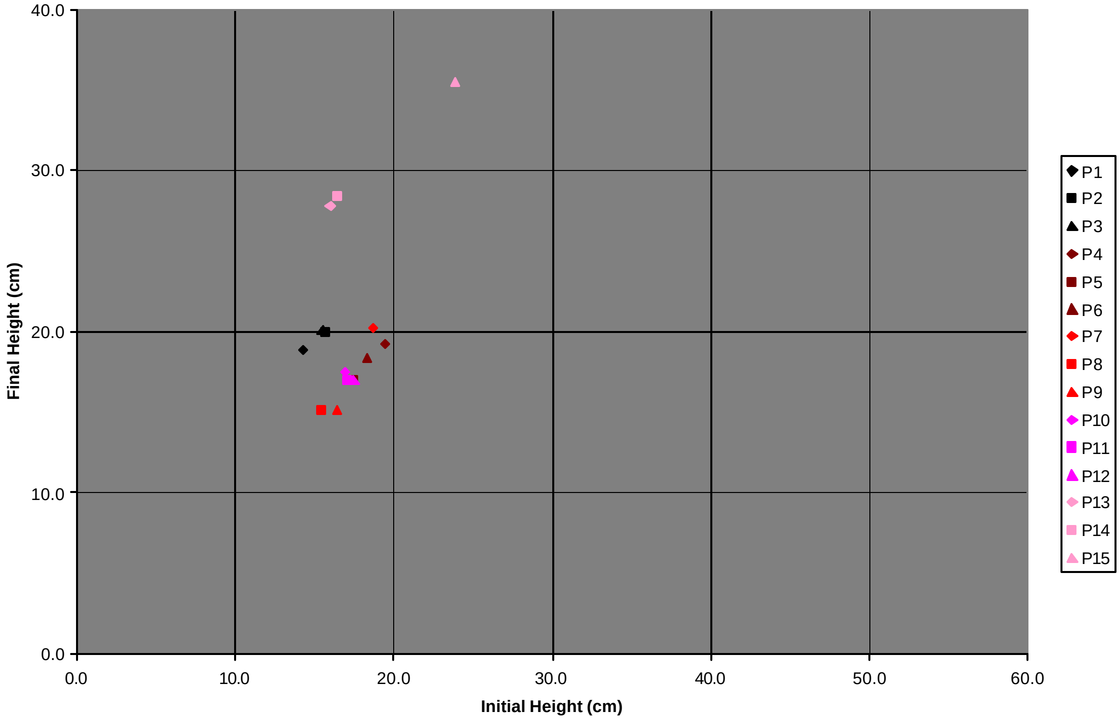
Graph 2: Douglas fir final height vs. initial height



Graph 3: Maple final height vs. initial height



Graph 4: Ponderosa pine final height vs. initial height



These results support the hypothesis in that trees that would grow the most would be those with the lowest levels of root chloride. However, it was expected that trees would exhibit more or less growth based on the concentration of root chloride. Instead, it seems that trees that received any $CaCl_2$ essentially did not grow at all, while trees that received no $CaCl_2$ grew much more.

4.4 Mass Measurements

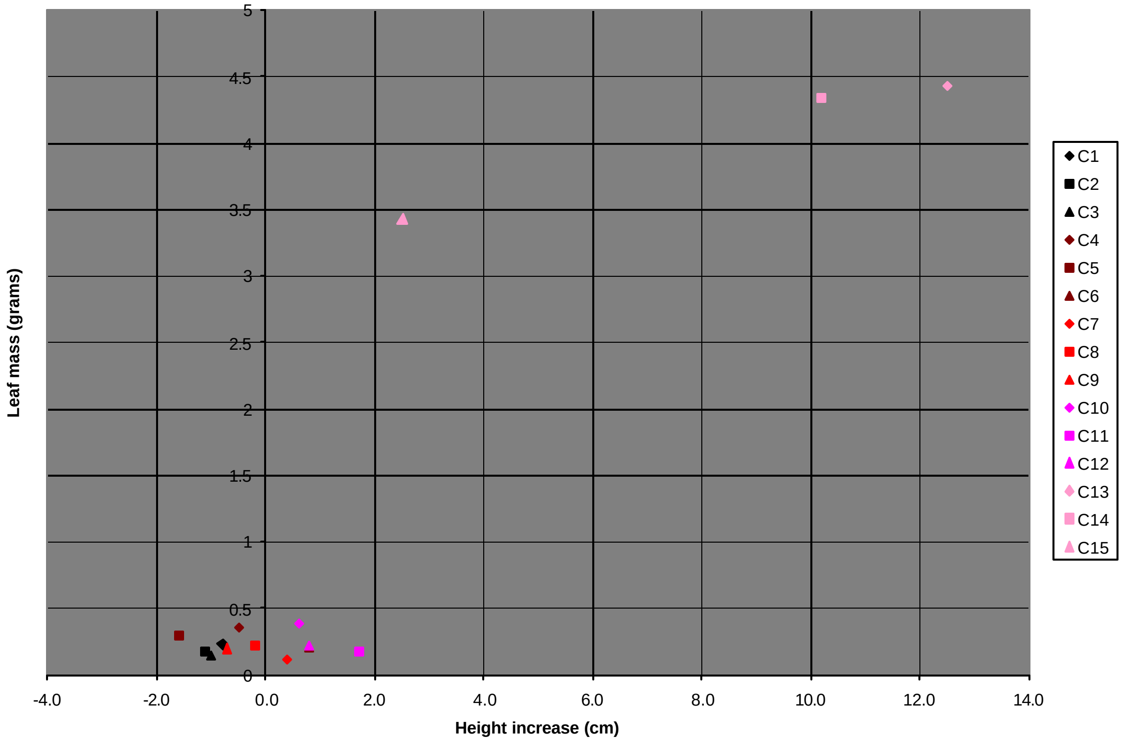
4.4.1 Leaf Mass

Trees given the control treatment exhibited the most leaf mass of all groups. Again, there does not appear to be a linear relationship between leaf mass and anti-icer concentration. Among deciduous trees grown in the greenhouse (cottonwood and maple) there was virtually no leaf growth among treatment groups receiving anti-icer. Because of this, no significant relationship was observed between leaf growth and anti-icer treatment concentration. Cottonwoods receiving any anti-icer developed leaves for 2-3 weeks, then leaf growth stopped and the immature leaves that had developed began to shrivel (see Appendix 1: Photographs). Maples given any anti-icer failed to even develop leaves. There did not appear to be any difference in leaf development for cottonwood and maple trees given different anti-icer concentration treatments—no cottonwood tree produced more than 0.39 grams of leaves, and maple trees receiving any anti-icer produced no actual leaves (leaf weight measurements were of leaf primordia).

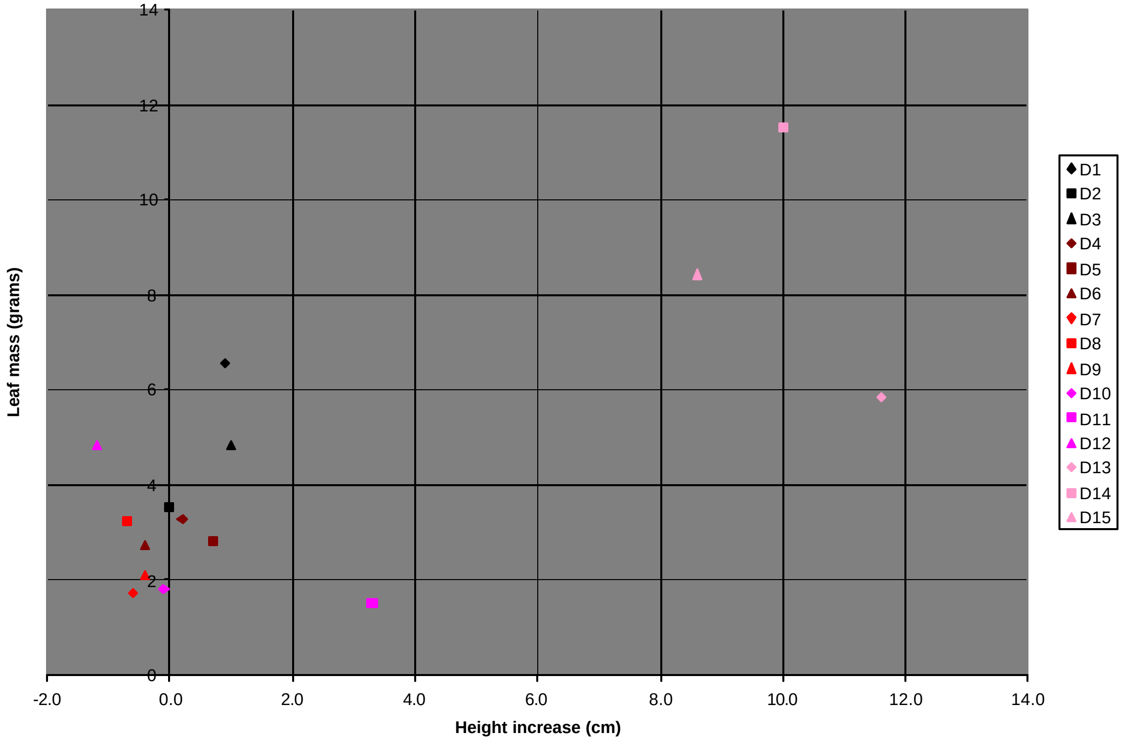
Coniferous trees (Douglas fir and Ponderosa pine) had already produced needles when the experiment began. At the end, trees from Groups 1-4 generally had produced less leaf mass than those of Group 5. This would be consistent with the hypothesis that the trees had been killed by the treatments early on, and any further needle development was due to the energy stored up in the cells prior to the commencement of the experiment. These results support the hypothesis that trees given anti-icer treatments would display less leaf growth, though the treatment concentrations appear to have been too high to elicit meaningful differentials of leaf development.

Graphs 6-9 plot leaf mass versus total height increase over the 8-week experimental period. Group 5 trees tend to align roughly around a diagonal plane, indicating a correlation between leaf mass and height increase.

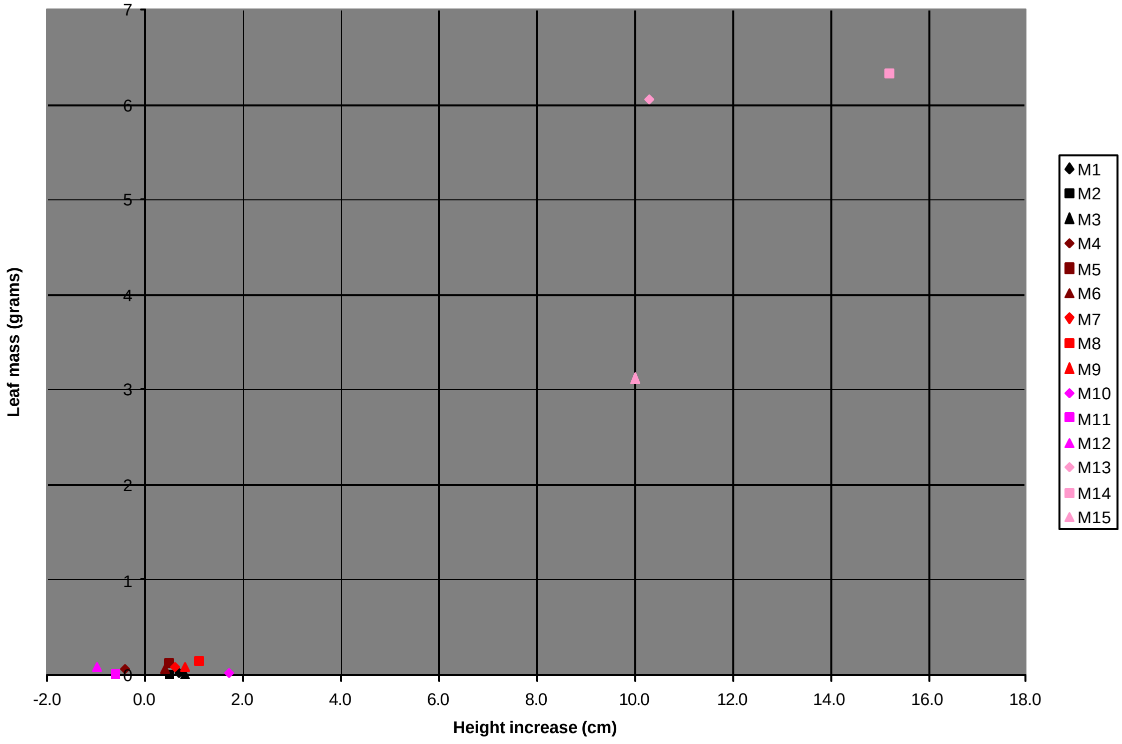
Graph 5: Cottonwood leaf mass versus total height increase



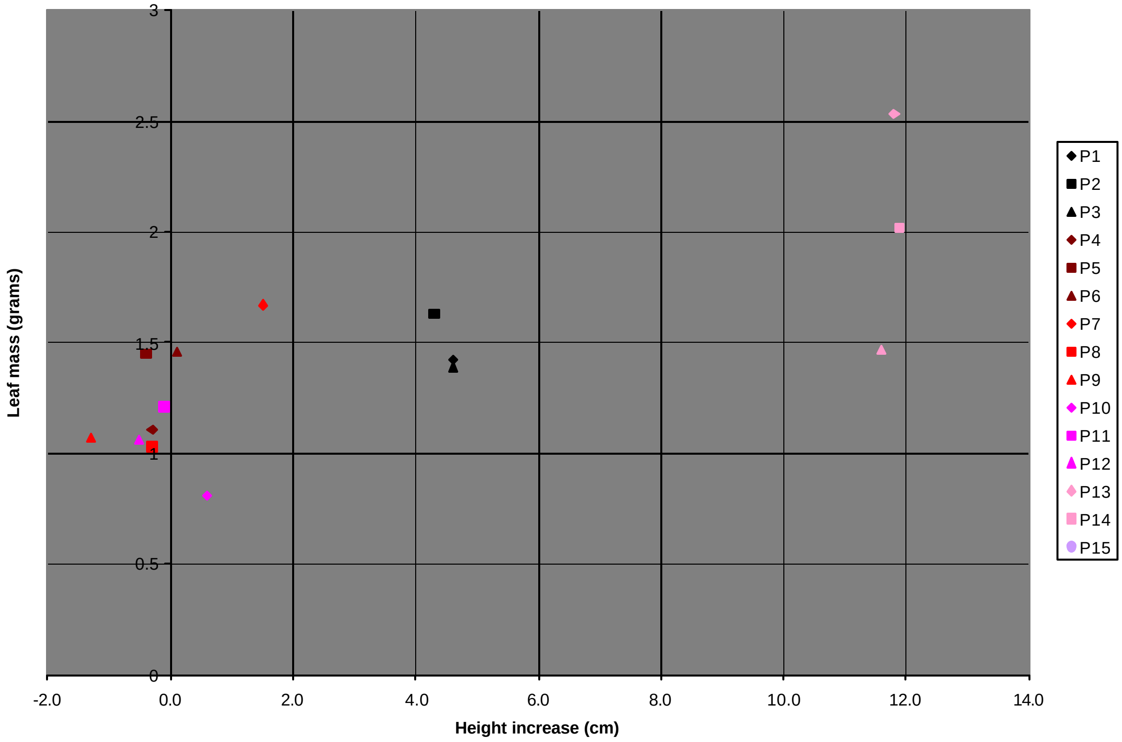
Graph 6: Douglas fir leaf mass versus total height increase



Graph 7: Big-leaf maple leaf mass versus total height increase



Graph 8: Ponderosa pine leaf mass versus total height increase

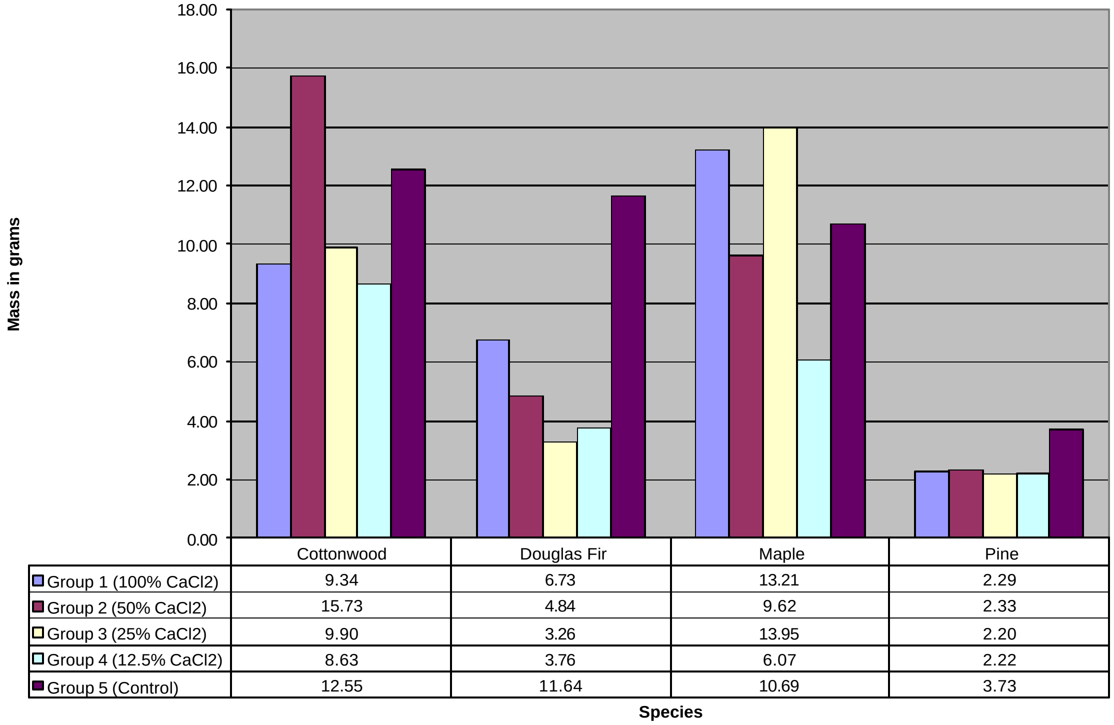


4.4.2 Stem Mass

Stems were weighed to determine different growth rates among trees receiving different concentrations of anti-icer treatments. While Group 5 trees produced the most stem mass, there seemed to be little, if any, difference among treatment groups. Further, it is doubtful that any real stem mass increase occurred, as it seems that trees receiving anti-icer treatments were killed by the treatments.

Group 5 stem masses averaged 12.55 grams for cottonwoods, 11.64 grams for Douglas fir, 10.69 grams for maple, and 3.73 grams for pines. There does not appear to be any clear trend of increasing mass with decreasing anti-icer treatment concentration. This experiment supported the hypothesis in that Group 5 trees produced the most stem mass, but the hypothesized decrease in stem growth corresponding with increasing anti-icer was not observed, probably due to the likely death of the trees.

Graph 9: Stem mass, arithmetic mean of three individuals of same species in same treatment group, measured in grams

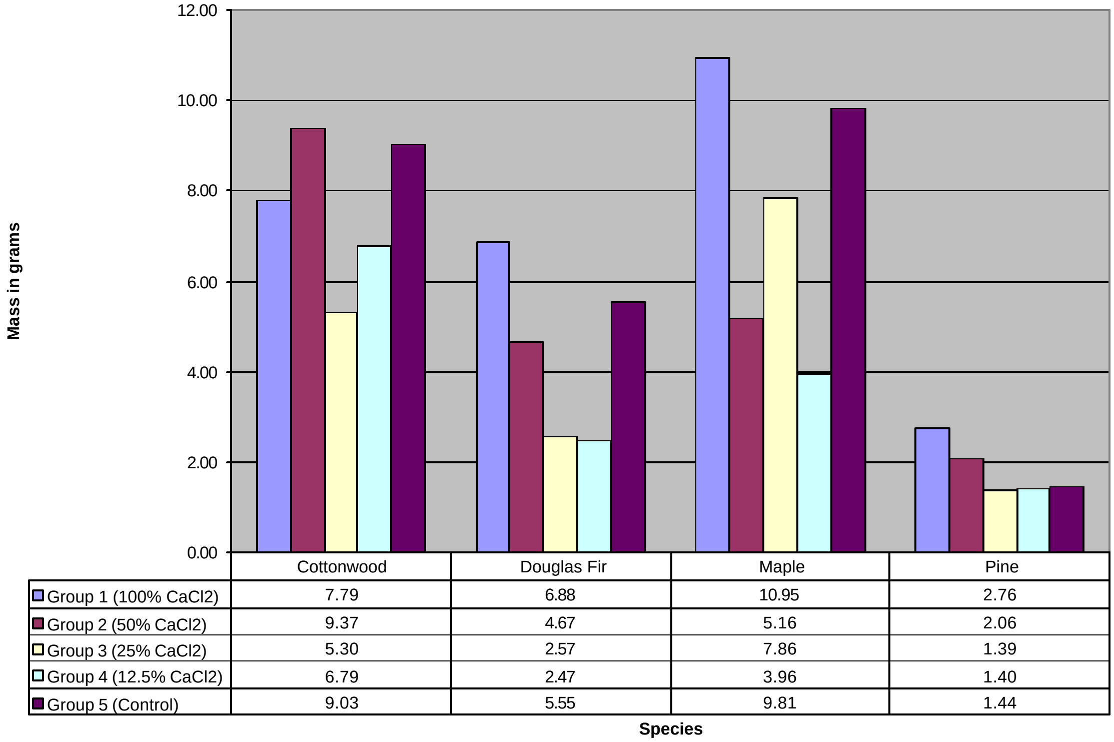


	Cottonwood	Douglas Fir	Maple	Pine
Group 1 (100% CaCl2)	9.34	6.73	13.21	2.29
Group 2 (50% CaCl2)	15.73	4.84	9.62	2.33
Group 3 (25% CaCl2)	9.90	3.26	13.95	2.20
Group 4 (12.5% CaCl2)	8.63	3.76	6.07	2.22
Group 5 (Control)	12.55	11.64	10.69	3.73

4.4.3 Root Mass

Roots were weighed to determine growth differences between concentrations of anti-icer treatments. Surprisingly, Group 1 trees developed the most root mass—an average of 7.79 grams for cottonwoods, 6.88 g for Douglas fir, 10.95 g for maples, and 2.76 g for pines. In none of the species did Group 5 produce the most root mass. It would seem from these results that, at least after an 8-week period, anti-icer treatments have no noticeable ill-effect on root growth. This was unexpected due to the preponderance of literature indicating severe root dieback as a result of anti-icer treatment. However, the differences between treatment groups were not very much, and it is difficult to pull any clear pattern from the data. If the trees did indeed die, then any apparent differences are unimportant and must be dismissed as random variation.

Graph 10: Root mass, arithmetic mean of three individuals of same species in same treatment group, measured in grams

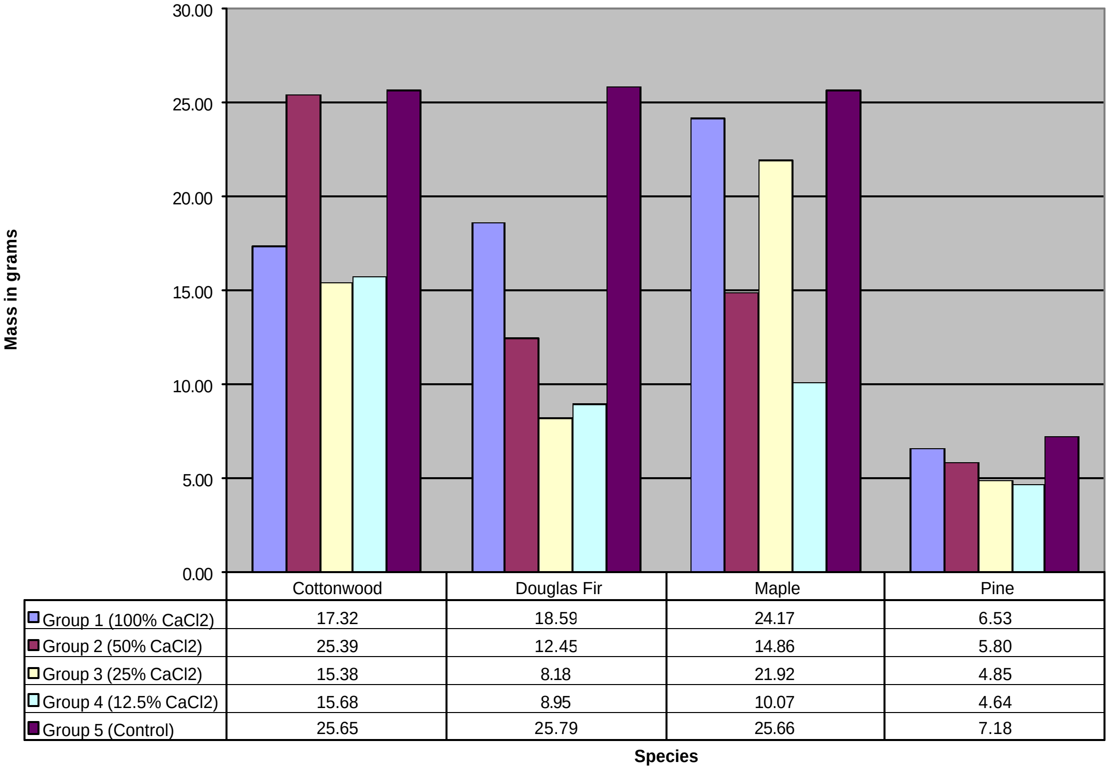


	Cottonwood	Douglas Fir	Maple	Pine
■ Group 1 (100% CaCl2)	7.79	6.88	10.95	2.76
■ Group 2 (50% CaCl2)	9.37	4.67	5.16	2.06
□ Group 3 (25% CaCl2)	5.30	2.57	7.86	1.39
□ Group 4 (12.5% CaCl2)	6.79	2.47	3.96	1.40
■ Group 5 (Control)	9.03	5.55	9.81	1.44

4.4.4 Total Mass

Leaf, stem, and root masses were combined to determine total weight of each tree in order to highlight differences in growth rates between trees receiving different concentrations of anti-icer. Again, since it appears that the trees in Groups 1-4 died as a result of the treatments, and since there is little that can be considered a pattern that emerges from the data of stem and root mass, total tree mass is not very helpful, and really only reflects the difference in leaf mass between groups. Trees from Group 5 produced the most total mass of all treatment groups—cottonwoods in the control treatment averaged 25.65 grams, Douglas firs 25.79 g, maples 25.66 g, and pines 7.18 g. Trees in Groups 1 through 4 less mass than those of Group 5, but did not show any obvious pattern.

Graph 11: Average total tree mass of each species within each treatment group

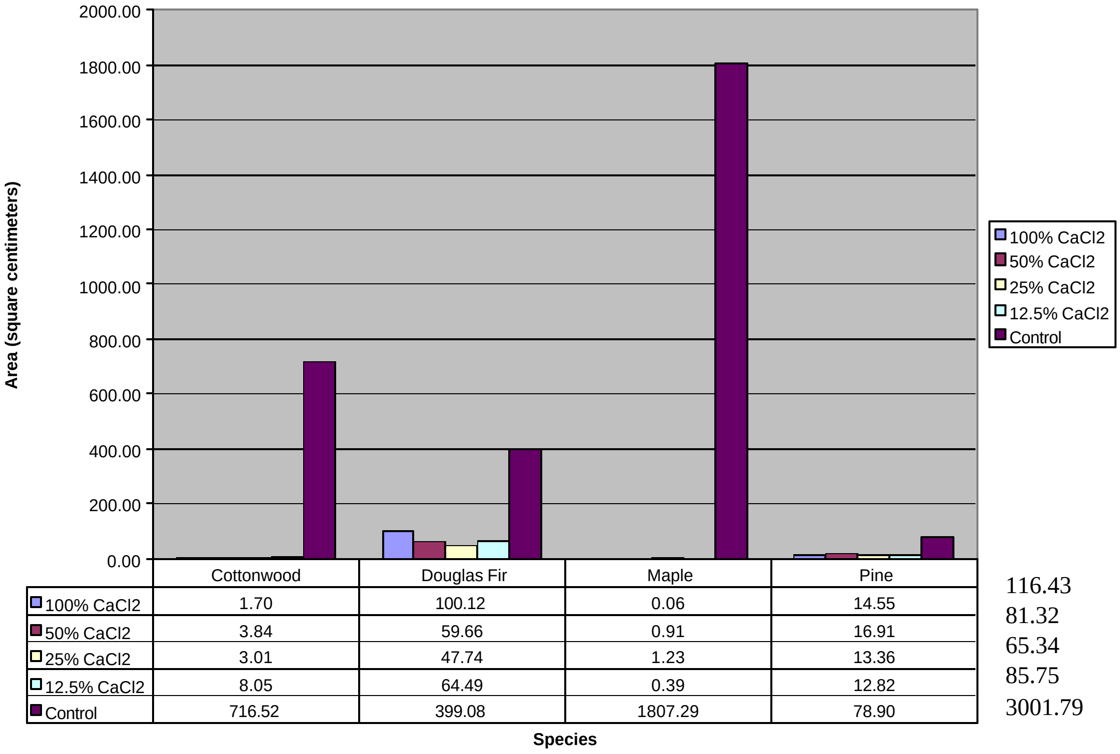


	Cottonwood	Douglas Fir	Maple	Pine
Group 1 (100% CaCl2)	17.32	18.59	24.17	6.53
Group 2 (50% CaCl2)	25.39	12.45	14.86	5.80
Group 3 (25% CaCl2)	15.38	8.18	21.92	4.85
Group 4 (12.5% CaCl2)	15.68	8.95	10.07	4.64
Group 5 (Control)	25.65	25.79	25.66	7.18

4.5 Leaf Surface Area

At the end of the experiment period, leaves from each individual tree were removed and total leaf surface area was calculated for each tree. Since trees in Groups 1-4 died, obviously Group 5 trees produced the most leaf area of all the treatment groups. Graph 13 shows leaf surface area averages from each species by treatment group. Graphs 14-17 plot leaf surface area against total height increase and show that trees that produced the most leaf mass also increased in height the most.

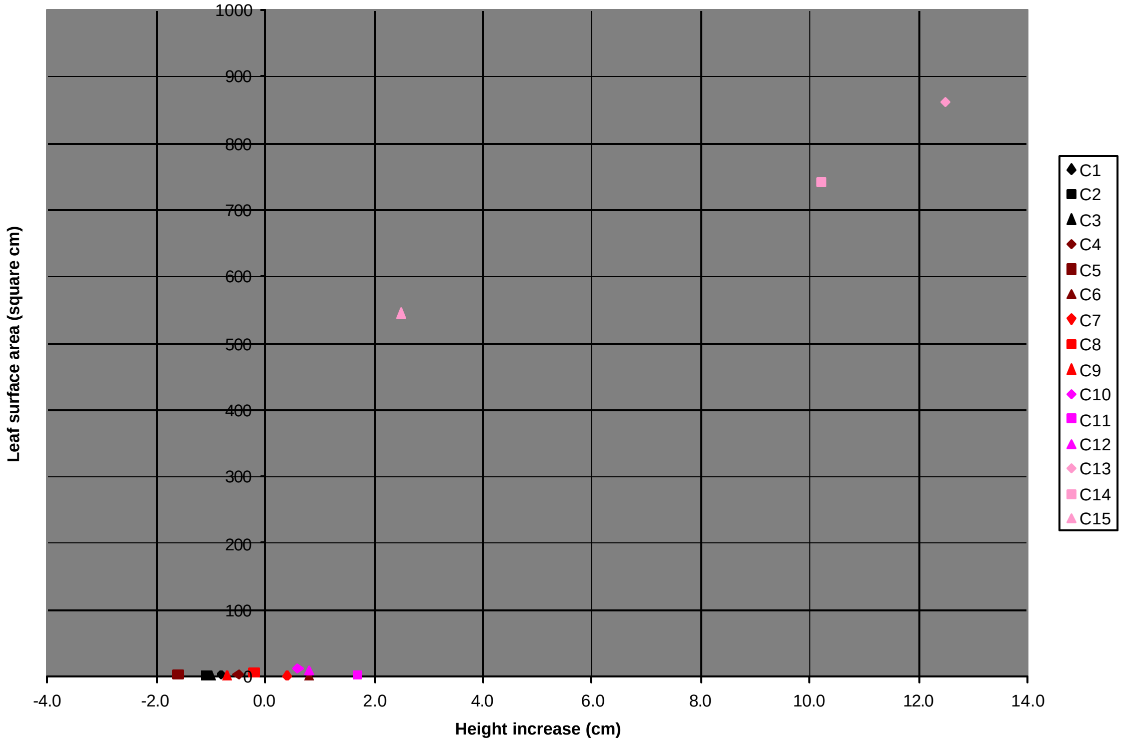
Graph 12: Leaf surface area



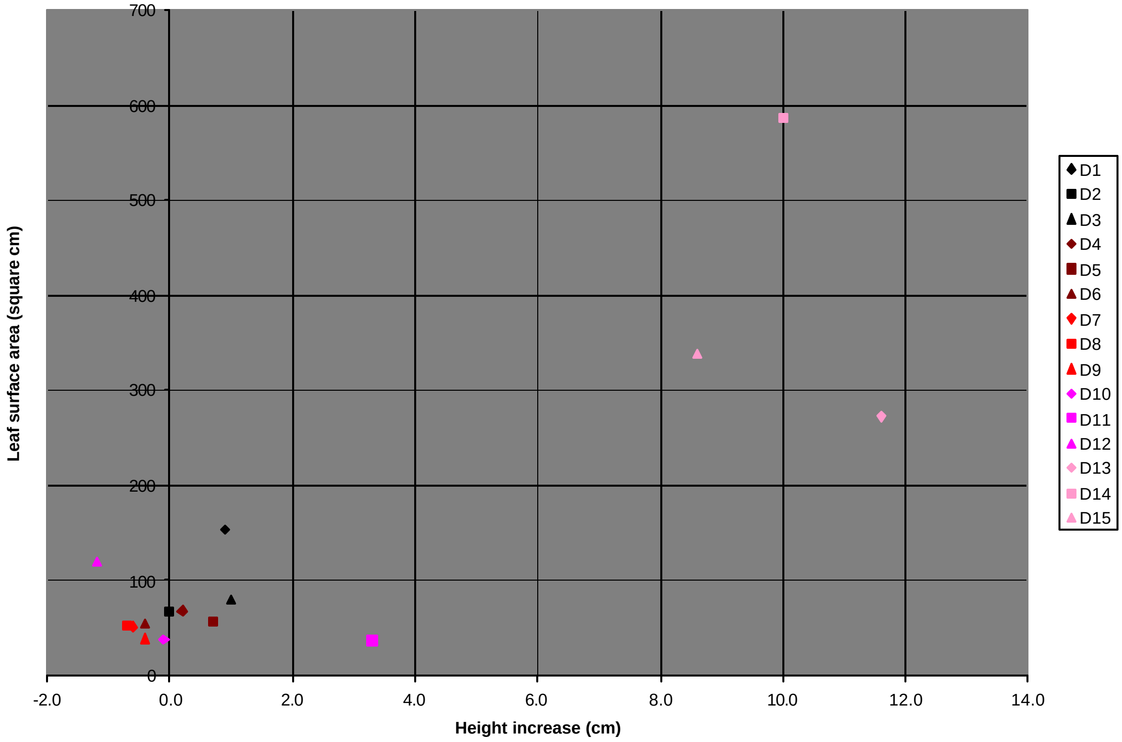
	Cottonwood	Douglas Fir	Maple	Pine
100% CaCl2	1.70	100.12	0.06	14.55
50% CaCl2	3.84	59.66	0.91	16.91
25% CaCl2	3.01	47.74	1.23	13.36
12.5% CaCl2	8.05	64.49	0.39	12.82
Control	716.52	399.08	1807.29	78.90

116.43
81.32
65.34
85.75
3001.79

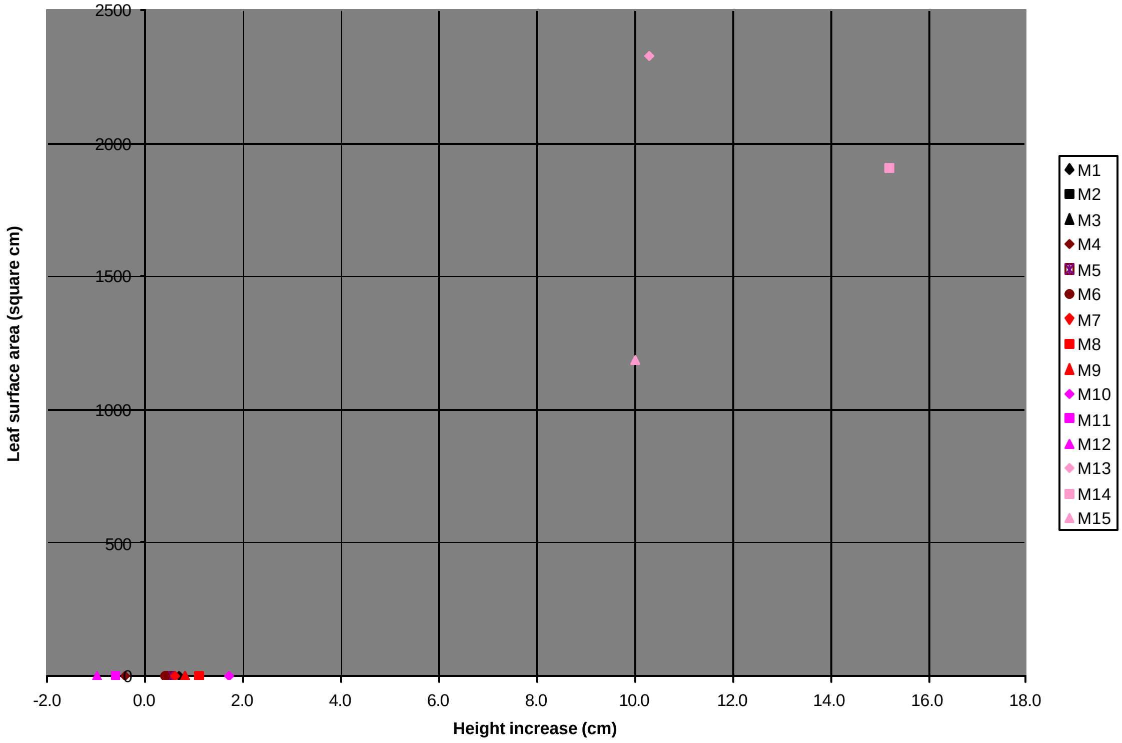
Graph 13: Cottonwood leaf surface area vs. total height increase



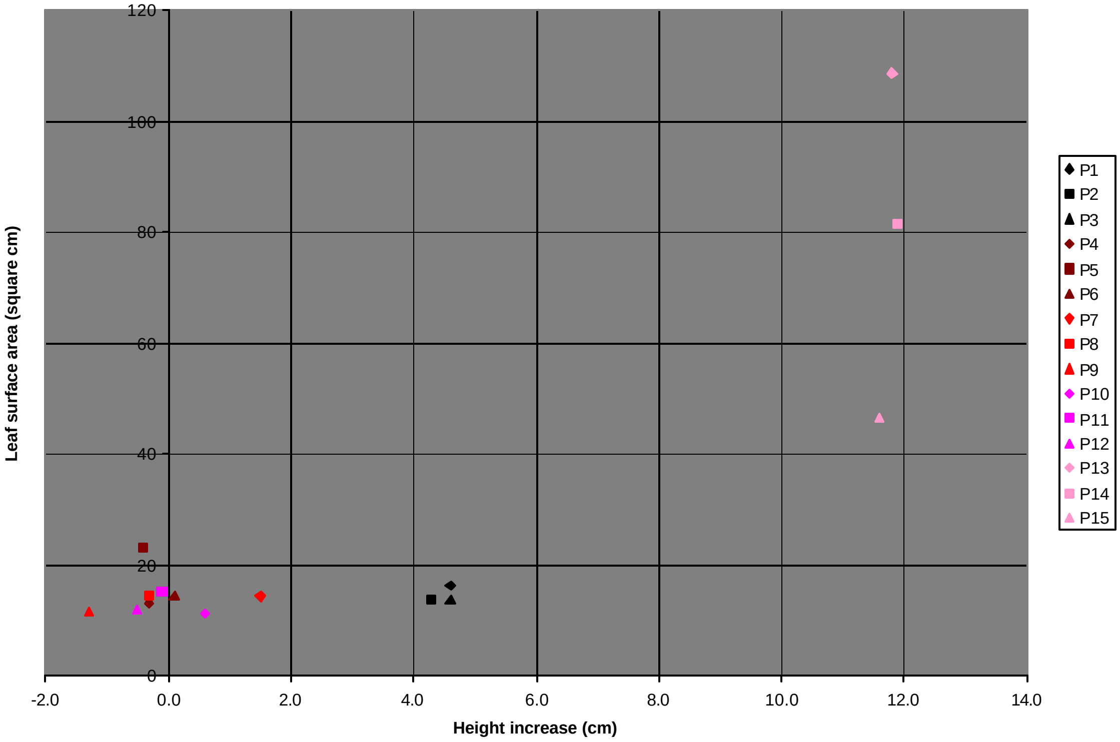
Graph 14: Douglas fir leaf surface area vs. total height increase



Graph 15: Big leaf maple leaf surface area vs. total height increase



Graph 16: Ponderosa pine leaf surface area vs. total height increase



5 DISCUSSION

5.1 Visual Observations

After only two weeks, Ponderosa pine and Douglas fir from Groups 1-4 began to dry out and turn brown—classic salt injury symptoms. Ponderosa needles were especially dry and brown, while Douglas fir needles seemed to grow slightly over the experiment period. Cottonwood trees started to produce leaves in all treatment groups; however, after a few weeks, the leaves stopped growing, turned brown at the tips, and dried out completely. Maple trees did not produce any leaves. The photographs show the obvious injury and lack of leaf development from trees receiving treatments containing anti-icer, regardless of the concentration.

The symptoms observed in the greenhouse are very similar in appearance to those observed along Highway 2 and Icicle Road around Leavenworth. The similar nature of the injury symptoms observed in the greenhouse experiments and in the field would support the hypothesis that anti-icers are the cause of the injury.

However, the severity of the symptoms observed in the greenhouse experiment and the growth pattern of the trees given anti-icer treatments make it fairly certain that even the lowest concentration treatment was lethal to the trees in Groups 1-4. Leaf break did occur in the cottonwood trees within a few weeks, and Douglas fir needles seemed to increase in size and quantity over the 8-week period. However, this could be explained by the trees receiving artificial light and elevated temperatures, just enough stimulation to begin bud break and use up the metabolic energy present when the experiment began. It is not clear that any growth or development that occurred in the trees in Groups 1-4 is a result of true biological growth, but could just be a physical process of cell expansion, after which the trees did not “grow” any further. Thus, since all the treatments were lethal, it is of little use to discuss the differences of the effects on trees observed between different concentrations of anti-icer, and any apparent differences are most likely little more than random variation.

5.2 Chloride Content

As the ion chromatograph results indicate, trees receiving higher concentrations of deicer treatment had higher root chloride content. Similarly, as logic would suggest, the soil of trees to which deicer was added had elevated chloride content, increasing with the concentration of deicer in the treatment solution. It is clearly reasonable to deduce that soil to which deicer is applied will have higher chloride content, and trees growing in that soil will also have higher chloride content.

Soil samples taken from the field do not seem to show any clear pattern of chloride content: values were too similar in affected and unaffected sites to discern any significant difference in chloride content. This is possibly a result of roadside soils being very well-drained, containing mostly sand and gravel, which thus retain little anti-icer residue. This is also a result of the small sample size.

Leaf samples, however, do seem to show a pattern. Leaves that obviously displayed injury symptoms consistently had higher chloride levels than those taken from the same area but displayed no injury symptoms. Again, the small sample size was part of the problem. More samples would improve the statistical power of this experiment. Samples were simply collected in two groups—injured leaves from areas known to receive deicer, and uninjured leaves from areas known not to receive deicer—and homogenized within each of the two groups. At the least, there appears to be a correlation between visual leaf injury and elevated chloride content.

Only a cursory visual examination of trees grown in the greenhouse is needed to see the injury symptoms in the trees receiving anti-icer treatments (see 1: Photographs). Trees receiving any anti-icer at all displayed severe injury symptoms, consistent with symptoms described in the literature: leaf browning, leaf scorch, limb dieback, marginal necrosis, etc. Since these symptoms only occurred in trees and soil that received anti-icer treatment and no injury symptoms were observed in Group 5, there is reason to believe that anti-icer is responsible for the injury symptoms. However, a larger sample size would be needed in order to generate statistically-significant results

5.3 Height Increase

Group 5 trees increased in height most out of all groups over the eight-week experiment period, as expected. However, it is not clear that any trees in Groups 1-4 truly increased in height at all. As stated above, they were likely killed by the anti-icer treatments.

This experiment supported the hypothesis that anti-icer treatments would stunt tree growth. However, the expected "gradient" of tree growth—higher concentration of anti-icer treatment would result in a progressively lower growth rate—was not observed. Again, this is likely explained by the trees having been killed by the anti-icer treatments.

5.4 Tree Growth Measurements

5.4.1 Leaf Mass

Clearly, Group 5 trees produced far more leaf mass than that of Groups 1-4. This, again, is mostly due to the deaths of all trees in Groups 1-4. Thus, the only real insight that this and the following mass measurements give into the effect of anti-icers on the greenhouse trees is that the doses were above lethal levels. For that reason, it is unnecessary to discuss stem and root mass.

A cursory observation at the end of the experiment would have led one to believe that the deciduous species fared much worse than the coniferous species, since the deciduous trees had no leaves of which to speak, while the coniferous trees at least had needles, brown and shriveled though they may have been. However, it must be noted that none of the cottonwoods or maples used in this experiment had developed any leaves by the beginning of the experiment, while the coniferous trees already had needles. It is possible that treatments had equally devastating effects on both deciduous and coniferous species, but since the coniferous trees had already produced needles, they appeared less affected by the treatments.

5.4.2 Stem Mass

Due to the mortality of the trees, discussion of stem mass measurements is unnecessary.

5.4.3 Root Mass

Due to the mortality of the trees, discussion of stem mass measurements is unnecessary.

5.4.4 Total Mass

Without being able to weigh trees before the experiment period and after, the possibility that the average weight of trees in Group 5 was initially higher by random chance, and the average weight of trees in Group 4 was lower, cannot be eliminated. However, it can be assumed from these experiments that anti-icer can be lethal to trees in sufficient quantity. It can therefore be assumed that anti-icer is detrimental to tree growth. If it can kill the trees, it likely can retard growth in lower quantities.

5.5 Leaf Surface Area

If the treatments killed trees in Groups 1-4, then leaf surface area is irrelevant. Any growth is simply the tree using up all the energy it had stored up in last-gasp growth efforts. Only Group 5 (the control group) reflects true growth.

6 CONCLUSION

6.1 Summary of Findings

The scale of this experiment was too small to produce statistically-powerful results or make any claims to scientific certainty. Further, the likelihood that anti-icer treatments were lethal to Groups 1-4 renders any apparent growth comparisons meaningless. The main finding of this experiment was that the anti-icer $CaCl_2$ is lethal to trees if present in excess.

Other general observations support this conclusion:

- $CaCl_2$ added to soil has a detrimental effect on growth of trees growing in that soil.
- Chloride levels are significantly higher in soil to which $CaCl_2$ is added.
- Chloride levels are significantly higher in root tissue of plants growing in soil to which $CaCl_2$ is added.
- All trees that displayed retarded or aborted leaf development also had elevated soil and root tissue chloride levels.

As to the question of whether anti-icer liquid could be the cause of injury symptoms observed around Leavenworth, consider the findings: Trees grown in the greenhouse that were given $CaCl_2$ treatments were killed. Ion chromatography tests clearly indicate that trees given $CaCl_2$ treatments had severely elevated soil and plant tissue chloride levels. Trees with elevated soil and plant tissue chloride levels also exhibited severe injury symptoms, similar to those observed in Tumwater and Icicle Canyons. Leaves from trees observed in both locations to have injury symptoms also had elevated chloride symptoms. It is clearly reasonable to believe that $CaCl_2$ highway anti-icer can be detrimental to trees in high concentrations. Though it cannot be concluded from this experiment with scientific certainty that anti-icers are the cause of observed foliar injury around Leavenworth, since the experiments were conducted in a greenhouse/laboratory setting, yet considering the chronology and distribution of the observed symptoms, the existing body of scientific literature on the topic, and the findings of this experiment, it is reasonable to consider it quite possible, if not likely, that the leaf injury symptoms observed around Leavenworth are due, at least in part, to $CaCl_2$ highway anti-icer.

6.2 Study Design Flaws

While this study shed some light on the question of how highway anti-icers affect roadside trees, the study could have been improved upon in a number of ways. A larger sample size for the greenhouse experiments would have yielded more statistically powerful data that could be analyzed more quantitatively. As it was, the population of 60 trees was, in effect, divided up into 20 groups of three individuals each. If there had been more individuals in each group, an effective statistical analysis could have provided more powerful results.

Additionally, the anti-icer treatments given to the trees were, in retrospect, far too strong. Even the lowest concentration of anti-icers appeared to have killed the trees. Had each succeeding the concentration been one-tenth of the previous, rather than one-half, there may have been more of a gradation of response to the treatments, rather than simply killing each tree from Groups 1-4.

It may have also been more enlightening had the greenhouse experiment been conducted over a longer period of time. The trees were given eight weeks to grow, though this time frame was chosen largely because of time constraints related to the academic semester and the observation that all trees in Groups 1-4 appeared to have died within 4-5 weeks. Had they been given more time to grow, along with lower concentrations of anti-icer application, there may have been a more visible pattern of response. However, with treatment concentrations that were used, more time would not have made a difference, as the trees appear to have been killed within a few weeks.

Well-thought-out field studies would have contributed significantly to this study as well. One field study that was considered was to work with the WSDOT and have anti-icers applied further up the Icicle than normal for one winter, then observe leaf development of trees along that stretch of road the following growing season. However, this was not practicable due to geographical distance from the study area.

6.3 Further Study

Unfortunately, due to the brief nature of this study, not all pertinent questions were adequately addressed. However, it is clear that further study into the environmental effects of highway anti-icers is warranted. A more extensive study of chloride levels of trees observed to have injury symptoms is needed, such as further ion chromatographic analysis of field samples of both apparently affected and unaffected trees—soil, leaf tissue, root tissue, etc. These chloride levels could then be correlated with treatment quantities or distance from the road.

Another enlightening study would be to observe trees along highways that do not receive anti-icer treatment, and compare visual observations of leaf conditions. Do symptoms occur along roads that do not receive anti-icer treatment? Certainly, along the two particular roads observed in this study, symptoms clearly coincided with the stretches to which anti-icer is applied and ended abruptly when anti-icer application ended. However, a study that focused on a larger set of roads is warranted.

Leaf injury among trees along Hwy 2 in Tumwater Canyon was much more severe than on those along Icicle Road in Icicle Canyon. One possible explanation is the speed limits on roads in the respective canyons. Hwy 2 along Tumwater Canyon has a speed limit of 50, while Icicle Road has a speed limit of 35. Cars driving at high rates of speed likely spray melted snow further than cars traveling slower. Also, there is more traffic on Hwy 2 than on Icicle Road, which is a dead end. Thus, it is possible that the more severe symptoms seem in Tumwater Canyon are due to the higher speed limit and more cars to spray the melted snow/deicer liquid further into the vegetation along the side of the road. However, this question was not addressed in this study. A study inquiring about the effects of traffic speed and distance of spray and severity of symptoms would be interesting.

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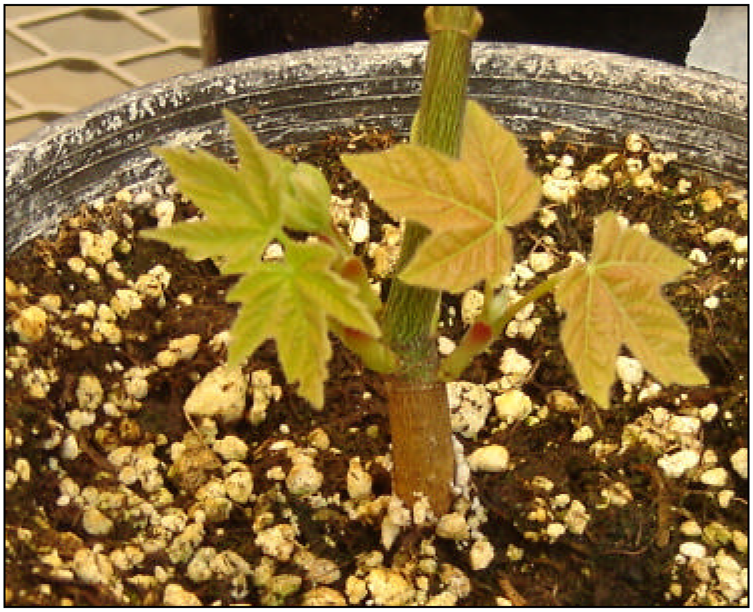
APPENDIX A: PHOTOGRAPHS

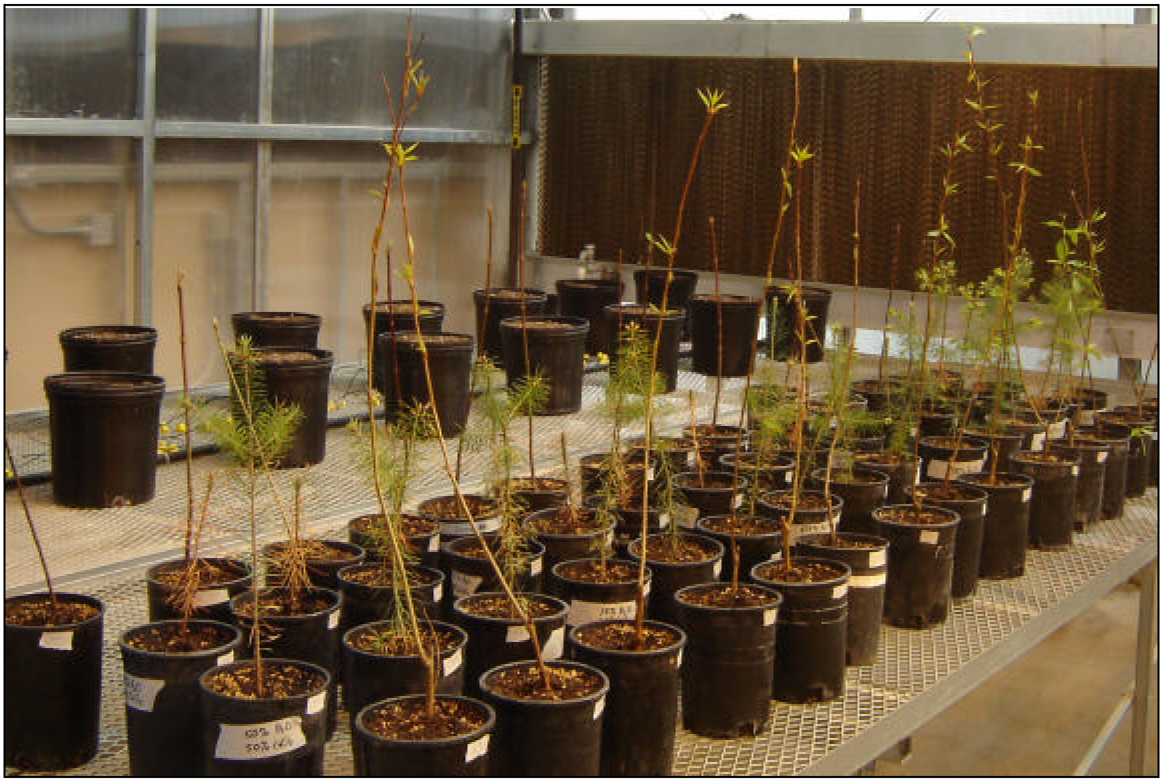
Photograph 1: February 25, all groups

Photograph 2: February 25, Douglas Fir Group 1


Photograph 3: March 4, Ponderosa pine Group 1


Photograph 4: March 4, Maple Group 5

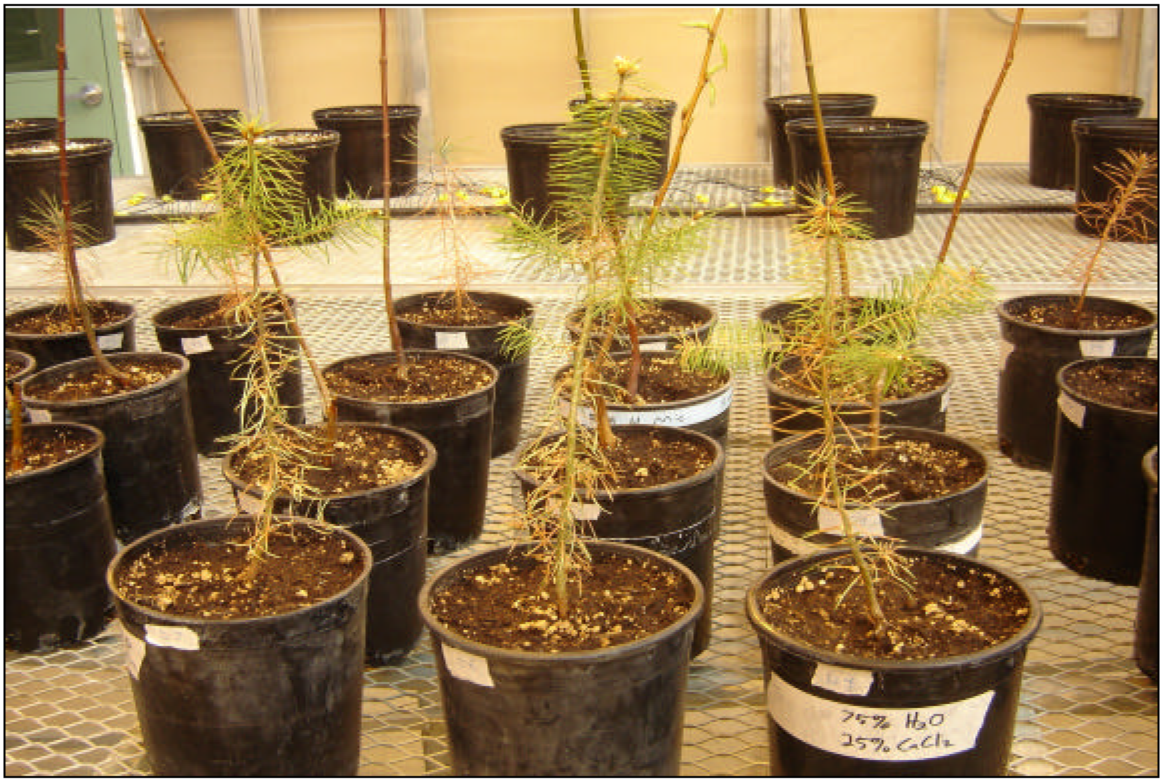
Photograph 5: March 4, all groups



Photograph 6: March 11, all groups

Photograph 7: March 11, Group 5

Photograph 8: March 11, Group 4 Ponderosa pine



Photograph 9: March 11, Group 3

Photograph 10: March 18, all groups

Photograph 11: March 18, Group 1

Photograph 12: March 18, Group 2 cottonwood leaves

Photograph 13: March 18, Douglas fir Group 4

Photograph 14: March 18, Douglas fir Group 3

Photograph 15: March 18, Douglas fir Group 1

Photograph 16: March 25, Cottonwood Groups 5, 4, 3, 2, and 1

Photograph 17: March 25, Douglas fir Groups 5, 4, 3, 2, and 1

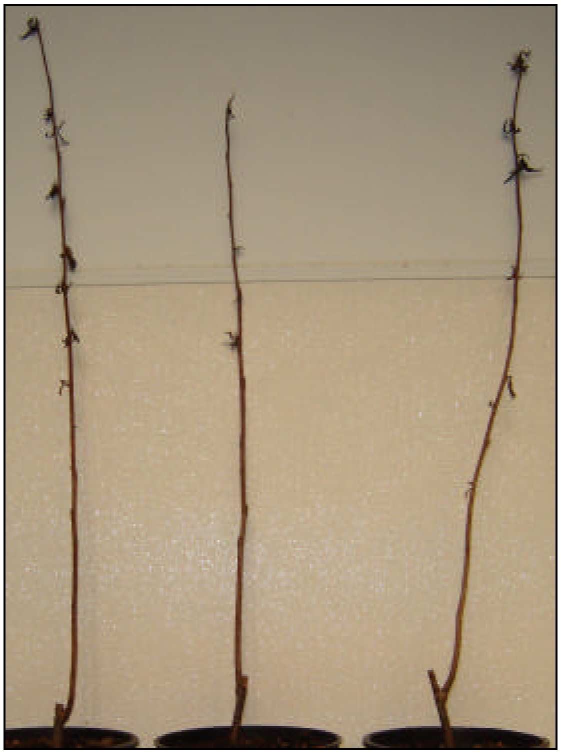
Photograph 18: March 25, Maple from Groups 5, 4, 3, 2, and 1

Photograph 19: March 25, Ponderosa pine, Groups 5, 4, 3, 2, and 1


Photograph 20: April 16, Cottonwood Group 1


Photograph 21: April 16, Cottonwood Group 2


Photograph 22: April 16, Cottonwood Group 3


Photograph 23: April 16, Cottonwood, Group 4

Photograph 24: April 16, Cottonwood Group 5

Photograph 25: April 16, Douglas Fir Group 1


Photograph 26: April 16, Douglas Fir Group 2


Photograph 27: April 16, Douglas Fir Group 3

Photograph 28: April 16, Douglas fir Group 4

Photograph 29: April 16, Douglas fir Group 5

Photograph 30: April 16, Big-leaf Maple Group 1

Photograph 31: April 16, Big-leaf Maple Group 2

Photograph 32: April 16, Big-leaf Maple Group 3

Photograph 33: April 16, Big-leaf Maple Group 4


Photograph 34: April 16, Big-leaf Maple Group 5


Photograph 35: April 16, Ponderosa Pine Group 1

Photograph 36: April 16, Ponderosa Pine Group 2

Photograph 37: April 16, Ponderosa Pine Group 3

Photograph 38: April 16, Ponderosa Pine Group 4

Photograph 39: April 16, Ponderosa Pine Group 5

Photograph 40: Injury symptoms along Icicle Road, mid-late summer 2004

Photograph 41: Injury symptoms along Icicle Road, mid-late summer 2004

Photograph 42: Injury symptoms in big-leaf maple leaves: browned, curled leaf margins

Photograph 43: Injury symptoms in big-leaf maple leaves: browned, curled leaf margins