NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM REPORT **170**

EFFECTS OF DEICING SALTS ON PLANT BIOTA AND SOIL

EXPERIMENTAL PHASE

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MAINTENANCE, GENERAL

TRANSPORTATION RESEARCH BOARD
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WASHINGTON, D.C. 1976

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

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The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the Academy and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are responsibilities of the Academy and its Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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FOREWORD

By Staff
Transportation Research Board

Use of sodium chloride and calcium chloride to aid in the removal of snow and ice from roadways has become an integral part of normal highway maintenance operations in areas of the United States that experience significant snowfall. As a supplement to *NCHRP Report 91,* "Effects of Deicing Salts on Water Quality and Biota—Literature Review and Recommended Research," this report describes the conduct and findings of the experimental phase of the investigation on the effect of deicing compounds on roadside vegetation. It contains information from (a) laboratory and greenhouse studies on the physiological effects of calcium, sodium, and chloride ions on plant growth and (b) field studies on the actual effects of calcium chloride and sodium chloride on specific woody plants and grasses. The latter will be particularly useful to highway personnel responsible for roadside landscaping and maintenance. In view of the increasing concern about contamination of the roadside environment, many other highway engineers, administrators, planners, and contractors, as well as persons outside the highway field, may also find it of interest.

It is imperative, in the interest of both safety and maximum utilization of the investment in highway facilities and motor vehicles, that roadways be maintained relatively free of ice and snow during the winter season. To accomplish this objective, highway maintenance organizations have found it necessary to use large quantities of deicing compounds, the most economical and readily available being sodium chloride and calcium chloride. The increasing use of these deicing salts has raised questions concerning the extent of certain detrimental effects on pavement surfaces, motor vehicles, roadside vegetation, water quality, and wildlife attributed to their use. As approaches to alleviating the problems associated with deicing salts, several NCHRP research projects have considered alternate deicing materials, additives to the commonly used salts, non-chemical methods for removing snow and ice, and special coatings to protect pavements and metal.* At present it does not appear likely that reliable and economical methods for ice and snow removal from highways that do not depend extensively on the use of sodium chloride and calcium chloride will come into common use in the foreseeable future.

* *NCHRP Report 4,* "Non-Chemical Methods of Snow and Ice Control on Highway Structures"; *NCHRP Report 16,* "Protective Coatings to Prevent Deterioration of Concrete by Deicing Chemicals"; *NCHRP Report 19,* "Economical and Effective Deicing Agents for Use on Highway Structures"; *NCHRP Report 23,* "Methods for Reducing Corrosion of Reinforcing Steel"; *NCHRP Report 27,* "Physical Factors Influencing Resistance of Concrete to Deicing Agents."

The study "Effects of Deicing Compounds on Vegetation and Water Supplies," undertaken by the Department of Agronomy of Virginia Polytechnic Institute and State University, involved (1) a literature review and survey covering the entire problem and (2) an experimental program with the specific objectives of determining the actual effects of deicing compounds on vegetation and soils along highways and determining means of counteracting these effects. *NCHRP Report 91,* "Effects of Deicing Salts on Water Quality and Biota—Literature Review and Recommended Research," covers the first phase of the study. In addition to providing highway agencies with an evaluation of previous research in the problem area, it served as background for the experimental phase of the project concerning roadside vegetation. The current report covers the laboratory and field experimental program conducted as the second phase of the project.

It has been shown that extensive use of deicing salts can result in contamination of roadside soils and injury to plant life. However, it was also determined that soil contamination and injury to plant life does not occur where there is adequate drainage of surface runoff from the roadside. Actually, when they are set back 30 feet from the pavement edge to conform with current safety standards and the *AASHTO Landscape Design Guide* (1965 Edition), there is little likelihood of deicing chemicals affecting roadside trees along straight roads. Greater setbacks are usually required on curves to provide adequate sight distance.

The data reported herein show marked differences in tolerance of the various trees, shrubs, and grasses included in the controlled field study to the ions in deicing salts. The honey locust deciduous tree, privet and honeysuckle deciduous shrubs, juniper evergreens, and Kentucky 31 tall fescue grass were all found to be quite resistant to rather heavy applications of deicing salts. Tulip poplar, green ash, rose, spirea, hemlock, and Kentucky bluegrass were all seriously injured by much lighter applications. It was also found that fertile soils, in particular those high in phosphate, reduce injury from deicing salts. This information will be of direct benefit to persons required to select plantings for areas where deicing salt contamination cannot be prevented.

The scope of the project did not permit determination of salt tolerance for a wide range of plant species used in various parts of the country. It did, however, (a) demonstrate that some plants are highly tolerant to the ions in deicing salts and (b) develop procedures (both laboratory and field) for determining the tolerance. As a result, it provides a basis for determining the tolerance of local plant species in different regions and, if the problem persists, developing more resistant species.

CONTENTS

ACKNOWLEDGMENTS

The research reported herein was performed under NCHRP Project 16–1, "Effects of Deicing Compounds on Vegetation and Water Supplies," by the Department of Agronomy, Virginia Polytechnic Institute and State University, with Dr. R. E. Blaser, Professor of Agronomy, as Principal Investigator. He was assisted throughout the study by R. E. Hanes and L. W. Zelazny, then Research Instructors at VPISU. Both have subsequently received PhD degrees. Dr. Hanes is now Vice President, U.S. Testing Company, Memphis, Tenn.; Dr. Zelazny is Assistant Professor, Soils Department, University of Florida, Gainesville. K. G. Verghese, R. P. Bosshart, E. W. Carson, Jr., and D. D. Wolf, Research Instructors at VPISU, also assisted with portions of the study.

EFFECTS OF DEICING SALTS ON PLANT BIOTA AND SOIL
EXPERIMENTAL PHASE

SUMMARY

This report covers the experimental phase of an investigation of the effects of deicing salts on vegetation and water supplies. The investigations involving roadside and other environments coupled with laboratory and greenhouse research give data and interpretations on the influence of two deicing salts (sodium chloride and calcium chloride) on the chemical composition of soils and on the morphological and physiological effects of various woody plant species and grasses. Conclusions and applications concerning the findings are included.

Investigations along US 7 in Vermont showed that highway deicing practices increased the concentrations of sodium and chloride and the specific conductance in a Vergennes soil in the roadside area on the low side of the highway. Concurrently, silver maples in the area suffered extensive decline and death. Along the opposite (high side) of the highway, trees were healthy and soils had low specific conductivity and low deicing salt ion contents.

In 1966, eighteen woody species were planted in replicated plots and treated with deicing salts so that salt movement and accumulation in soil horizons, as well as salt ion absorption and injury to plant issue, could be investigated. These experiments were established on three different types of soils, one in each of three physiographic regions in Virginia. Sodium chloride and calcium chloride were applied to these plots on various occasions during the winter in order to investigate the influence of the rate of their application on woody plants varying in age. The plants were ranked according to degree of injury and photographed; also, leaf and stem tissues of plants as well as soils were analyzed for salt ion content.

Thornless honey locust was tolerant to both sodium and calcium chloride and remained healthy at high salt applications during the 4-yr experiment. European white birch, sugar maple, and redbud were moderately tolerant to both deicing salts; however, when subjected to high rates of salt application, many of the trees failed to survive after the first winter. Green ash and tulip poplar were injured by both salts, even at low salt applications.

Privet and honeysuckle were the most tolerant deciduous shrubs, surviving with the highest salt applications. Forsythia and weigela were intermediate in tolerance but were severely damaged. Spirea and rose were sensitive to both deicing salts, resulting in complete leaf drop, dead tissues, and death. Tolerances tended to increase with age and size of plants.

Of the 6 species of evergreen trees and shrubs in the experiment, Pfitzer juniper, creeping juniper, and Adam's needle were very tolerant and showed little injury even at the highest rates of salt application. White pine, Norway spruce, and Canadian hemlock were salt sensitive to the degree that even the lowest rates of salt application during one winter season caused their severe injuries and deaths the

next season. The degree of injury varied; at controlled rates of application, calcium chloride caused more injury to white pine, while sodium chloride caused more injury to hemlock.

For grasses, the reduction in yield from sodium chloride application was in the order of Kentucky bluegrass, bromegrass, red fescue, and Kentucky 31 fescue. Salt applications retarded top growth more than root growth, and leaf tip burn was most noticeable for Kentucky bluegrass and red fescue at all rates of sodium chloride application. Sodium and chloride absorption increased with increased rates of applying deicing salts. Kentucky 31 fescue had higher concentrations of sodium and chloride in tissue than did the other three grasses, indicating that Kentucky 31 fescue is more tolerant of these ions. Light sodium chloride concentrations increased root and top growth of Kentucky 31 fescue and bluegrass. Sodium uptake was reduced by potassium applications. Liberal and balanced fertilization tended to minimize the harmful effects of deicing salts on growth and maintenance of grass stands. Ions in fertilizers influence plant growth and its chemical uptake from deicing salts.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

SNOW AND ICE REMOVAL

Deicing salts are used extensively in the snowbelt states because highway agencies encounter public pressure to rapidly remove snow and ice from highways. Although mechanical means of snow removal are also used, the use of salts is the most economical and reliable method for removing ice and snow and preventing its accumulation. Most states and cities maintain bare pavement when possible on primary roads and streets to minimize traffic delays and accidents associated with hazardous driving on slippery highways. Parks, public and industrial sites, and homeowners also liberally use deicing salts to minimize hazardous situations during the winter season.

The amounts of deicing salts applied to roads and streets annually have increased dramatically for several reasons. The population explosion and rapidly increasing traffic volume, particularly in urban areas, have increased the need for maximum utilization of roadway facilities year around. Also, no suitable alternatives to salts have been developed. The use of salts is a controversial issue that has its supporting and opposing factions. One faction demands that roadways and walkways be kept free of snow and ice. Others strongly oppose the use of deicing salts because of the growing concern that their use causes detrimental effects, by means of pollution.

Declining and dying woody vegetation near highways has been associated with highway drainage waters bearing deicing salts. Many people have become concerned about this impairment of plant communities for environmental reasons and because they fear similar harmful effects of deicing salts might occur in animal biota. It is fortunate that all ions (chloride, sodium, calcium) present in the two commonly used deicing salts are essential for animals, including man. Although deicing salts are accumulating from year to year in water supplies, such as ponds and reservoirs, concentrations are too low to be harmful to wildlife, domestic animals, and man. Animals, for example, have congregated around salt licks, consuming excess quantities of salt, for generations; likewise, feeding salt to mammals in amounts exceeding nutritional needs has been a common practice with no adverse effects for generations. The kidney system of mammals effectively dissipates accumulations of digestive substances, such as salts. On the other hand, plants are often severely injured by continuous absorption of salt ions that concentrate in tissues in toxic amounts. Plants cannot eliminate toxic materials except through the inefficient mechanism of dropping leaves. Trees respond to increasing ion accumulations by first dropping small dead twigs, then larger limbs, and eventually by dying. However, it is known that plants differ sharply in salt tolerance and other adaptive characteristics. This report comprises a review and interpretation of the literature and gives recommendations for needed research on the effects of deicing salts on water supplies for domestic, agricultural, fish, and wildlife uses. In addition, current ice and snow control practices are reviewed, and the results of an extensive survey on the use of deicing salts by state highway and toll authorities are reported. Also included is a discussion on salts in soil environments and their influence on physiological and morphological responses of plants to salt stress, as well as a review of deicing salt injuries to roadside vegetation.

The experimental phase involves various investigations of different soil environments in several snow-belt states with laboratory support to diagnose the effects of two primary deicing salts (sodium chloride, commonly called rock salt, and calcium chloride) on soils and vegetation along highways and to make recommendations on the implementation of research findings. Specific research objectives were:

1. To obtain data on salt accumulation from soils of different physiographic regions along highways in some northern states.
2. To study the effects of deicing salts at various concentrations applied to soils of three distinct physiographic regions on the survival, growth morphology, physiology, and anatomy of woody and herbaceous plants.
3. To study the effects of salt concentrations and frequency of application on deciduous and evergreen plants in various stages of dormancy.
4. To study the effects of deicing salts on chemical and physical properties of soils and to study the movement and retention of salts therein.
5. To study the effects of various deicing salts on foliar and root absorption of water and plant nutrients and to study physiological effects within the plant at various temperatures, stages of growth, and other stress.
6. To ascertain the harmful effects on plants of newly developed deicing compounds and to make comparisons with deicing salts currently used.

Substantial information was obtained for all objectives with the exception of item 6. This objective was not investigated because new and suitable substitutes have not been developed. It was not within the scope of this project to produce substitutes for deicing salts.

To broaden the perspective and application of this investigation, experiments with various species of woody plants (deciduous and evergreen trees and shrubs) were conducted in various snow-belt states in widely different soil environments, geomorphic conditions, and climatic situations. Some of the experiments were located along highways in different states, where deicing salts were applied for snow and ice control by highway personnel, to investigate subsequent salt movement effects as shown by chemical analyses of soils and plants at various distances from pavements. For example, different species of trees were planted at various distances from pavements. Subsequently, tree and soil samples were taken periodically during the late winter-early summer season. Soil profiles were sampled at various depths and at diverse distances from pavements; leaves and stems of planted or existing trees were also sampled and subsequently analyzed for the presence of ions of various deicing salts.

Because it is impossible to control the amount, kind and frequency of applying deicing salts along highways where highway crews pursue normal snow and ice control and because of sharp variations in microenvironments with drainage patterns and distances from highways, three carefully controlled experiments were established in three physiographic regions of Virginia: mountainous region at Blacksburg, piedmont at Orange, and coastal plain at Warsaw. The soils on which the three sites were located were Groseclose, Nason, and Sassafras, respectively. A planting plot design consisted of 12 plots each of which held nine plants of six woody species with four replications. There were separate experiments of four replications each for three species groups: (a) deciduous trees, (b) deciduous shrubs, and (c) evergreen trees and shrubs. For the three locations, a total of 23,318 trees were planted. Two deicing salts (calcium chloride and sodium chloride) were applied at various rates and frequencies beginning with the 1966 winter for plantings made during early spring of that year. Some plots were left untreated for two to three years so that eventually studies could be made of salt effects on trees of various ages. The species were rated for salt tolerance or injury, and their stem and leaf tissues were analyzed for salt ion accumulations and were photographed. Soil profiles were analyzed at various depths and frequencies in order to determine the movement and leaching of ions with time after application of deicing salts. The replication and random assignment of deicing salts and plant species, as well as the careful control of salt applications, allowed for statistical verification of deicing salt injuries, or the lack of them, among the plant species.

Other experiments with woody plants were conducted in a greenhouse, growth chamber, or laboratories in order to investigate deicing salt ion effects on such physiological factors as photosynthesis and respiration as well as to determine antagonistic influences of ions in soils or solution cultures.

Experiments with perennial grasses were established on soils near Blacksburg and Warsaw, Va., in order to investigate the effects of various rates of sodium chloride application on grass yield, survival, injury to tissue, and absorption of salt ions within grasses both with and without nitrogen fertilization. One experiment was established in a sand culture in a greenhouse in order to measure salt tolerance, root and top growth, and salt ion uptake under low and high soil fertility. Another greenhouse experiment was established to investigate the interaction of fertility on grass uptake of sodium chloride, grass growth, and grass injury. The complementary effects in the presence of various mineral nutrient ions in the rooting medium on sodium and chloride absorption and growth was studied in a third experiment using a Groseclose silt loam soil. There is thus a need of studying plant biota with a view toward isolating salt-tolerant species and disclosing information on the physiological and morphological effects of salts.

This report deals with (a) the chemistry, concentration, and movement of ions from deicing salts in horizons of various soils and (b) the accumulation of deicing salt ions in plant tissue with concurrent effects on growth, physiology, and morphology of grasses and woody vegetation. Information on the salt tolerance differential among plant species in conjunction with data on composition of soils should be of aid in directing deicing salt applications and in planning highways and landscape designs such that injury to plants from salts is minimized. The harmful influence on plant biota of various ions in deicing salts is not well understood. Plant injury has been attributed to osmotic effects, mineral nutrient element imbalance, toxicity, or combination of these through soil mechanisms and root absorption. The salt ions causing injury to various plant species and comparative damage from salt spray on foliage and root absorption have been debatable.

RESEARCH APPROACH

NCHRP Project 16-1, "Effects of Deicing Compounds on Vegetation and Water Supplies," was divided into literature review and experimental phases.

The literature review phase has been published (*1*).

Various statistical designs with replicated and randomized treatment arrangements to subject data to statistical tests of significance were employed when possible.

It was necessary to develop laboratory techniques for rapid and reliable analysis. Analytical techniques for chloride analysis had to be arranged in a laboratory isolated from other research laboratories because of interference and adverse effects from ammonia.

ORGANIZATION OF THE REPORT

The first part of this report contains a brief presentation of the many findings along with conclusions and suggested application of the findings. The second part is composed of a series of ten appendixes discussing the nature, procedures, and results of the several experimental studies of the project. The reader is encouraged to read these for important details.

CHAPTER TWO

FINDINGS

The findings reported here are the results of laboratory and field investigations of two commonly used deicing salts (sodium chloride and calcium chloride) and their influence on soils and plant biota. This chapter (a) summarizes data concerning soil composition and salt injury to plant biota along highways where normal deicing salt practices were employed by highway departments; (b) deals with the injurious effects of deicing salts, applied at various rates and frequencies on three different soils, on 18 woody species and their compositions; (c) summarizes research on the growth, transpiration, and photosynthesis of three species of trees when subjected to various osmotic concentrations of deicing salts; (d) includes data on the salt tolerance of and sodium and chloride absorption by four types of grass, and also interrelates nitrogen fertilization and the influence of various mineral ions on grass growth and absorption of and tolerance to sodium chloride; (e) discusses the movement of deicing salt ions in various soil horizons as interrelated with soil chemical characteristics; and (f) summarizes information on salt spray and root absorption of ions from deicing salts.

INJURY TO PLANT BIOTA ALONG HIGHWAYS

Deicing salts applied to roads and streets can be carried by surface runoff into streams and waterways or they can infiltrate soils bordering treated highways. When soil infiltration occurs, ions of the deicing salts can flow with drainage or groundwaters, remain in soil solution, or become absorbed by soils. Therefore, salts can create an unpotable water supply, the loss of a soil's ability to support desirable plant growth, or both.

Salt injury to vegetation occurs with salt ion accumulation in plant tissues causing a general growth reduction followed by leaf scorch and curling, leaf drop, stem dieback, and a gradual decline in vigor, which results ultimately in death. Such damaged vegetation not only creates an unsightly condition that can decrease property value, but it also is contrary to established highway beautification programs and the general concern about aesthetic values. Such adverse effects from deicing salts also increase the cost of highway maintenance because of a need for replanting new highways and removing hazardous dead woody vegetation from old roadways. However, the extent to which deicing salts are directly responsible for plant injury is still a controversial subject.

The purpose of this portion of the investigation was to determine the distribution and movement of deicing salt ions bordering the highway at a site in Vermont and to determine the role of these salts in causing an extensive decline of silver maples in this highway environment.

The site near Shelburne, Vt., on US 7, once had approximately 250 trees, mostly mature silver maples, on both sides of the road about 15 ft from the edge of the highway. Because of the slope, water runoff occurs primarily to the east side of the road where the trees were damaged or dead. Trees on the west side of the road are growing vigorously. The Vergennes soil bordering the highway is moderately well-drained. Figure 1 shows this site in 1968.

Soil samples for salt ion analysis were taken from both sides of the highway midway along the slope on eight different dates. The samples were collected at 3-ft intervals away from the pavement and at 3-in. increments in depth.

On the east side of the highway, having tree deterioration, the average sodium and chloride contents in the soil and the specific conductivity of the soil extracts were larger than for the soil on the west side of the highway. The specific conductivity on the east side of the road was more than twice as high as that on the west side while the sodium and chloride in the soil were six and ten times higher on the east than on the west side of the road, respectively. The content of calcium on the two sides of the road was similar. The following tabulation shows that soil analyses for samples collected from the 9- through 21-ft distances from the highway and 0- through 12-in. depths on all eight sampling dates averaged:

ROADSIDE	SPECIFIC CONDUCTIVITY (μMHO/CM)[a]	CHLORIDE (PPM)[b]	SODIUM (PPM)	CALCIUM (PPM)
East	1045.9	268.4	243.4	59.4
West	482.1	26.8	40.2	73.4

[a] In micromhos per centimetre.
[b] In parts per million.

When tested on April 5, 1969, the largest salt concentration in the soil was 3 ft from the pavement on the east side of the highway. Specific conductivity of the soil was 3960 μmho/cm ($EC \times 10^{-6}$) and the quantities of sodium and chloride were 1080 and 2577 ppm, respectively. A specific conductance this large would be moderately saline and would restrict the growth of many plants. The osmotic pressure caused by the salt in the soil was approximately 1.5 atm. By the June 24, 1969, sampling date, the salt in the soil had diminished sharply; the osmotic effect at this date was less than 0.5 atm.

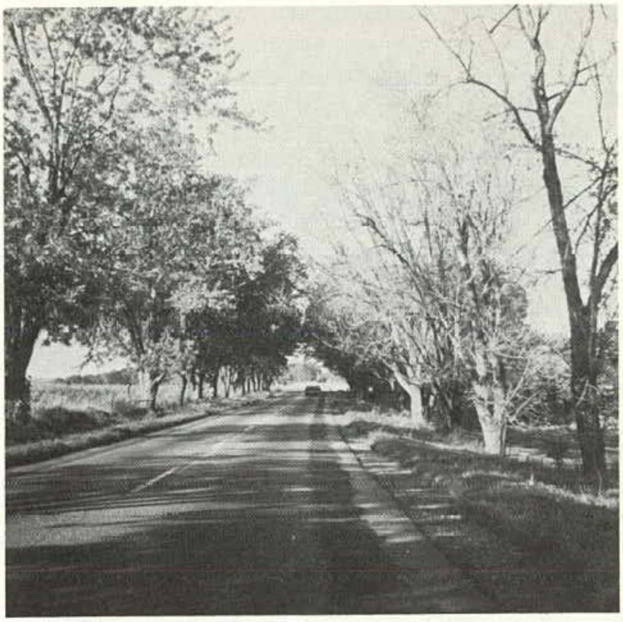


Figure 1. A portion of US 7 south of Shelburne, Vermont, showing the decline of silver maples located on the low side of the highway.

Leaf and twig samples from the silver maples were collected from both sides of the highway on six sampling dates over a 4-yr period. When analyzed for sodium and chloride, it was discovered that chloride concentrations averaged approximately three times greater in leaves and twigs of damaged trees (east side of highway) compared to those of healthy trees (Table 1). Chloride concentrations were higher in leaves than stems. However, chloride concentrations in both leaves and stems generally increased with the deterioration of silver maples.

Analysis showed sodium concentrations in leaves and stems averaged five to seven times greater for damaged trees on the east side of the road, which receive drainage waters with deicing salts, than for the healthy trees on the west side. However, even in the damaged trees, sodium

TABLE 1

ANALYSIS OF CHLORIDE AND SODIUM CONTENTS IN THE LEAVES AND STEMS OF DETERIORATING (ON EAST SIDE OF HIGHWAY) AND HEALTHY (ON WEST SIDE) SILVER MAPLE TREES

SAMPLING DATE	LEAVES				STEMS			
	CL		NA		CL		NA	
	EAST	WEST	EAST	WEST	EAST	WEST	EAST	WEST
9-14-66	0.83[a]	0.30	0.04[a]	0.01	0.36[b]	0.18	0.05[b]	0.01
9-15-67	0.70[a]	0.26	0.03[a]	0.01	0.94[a]	0.22	0.05[b]	0.01
6-20-68	0.67[a]	0.15	0.03[a]	0.01	0.13[a]	0.07	0.04[b]	0.02
9-13-68	1.18[a]	0.32	0.05[b]	0.00	0.19[a]	0.09	0.02[b]	0.01
4-5-69	—	—	—	—	0.20[a]	0.14	0.16	0.14
6-24-69	0.83[a]	0.16	0.08[a]	0.01	0.27[a]	0.11	0.06	0.01

[a] Significance at the 1-percent level.
[b] Significance at the 5-percent level.
Note: Statistical comparisons can only be made between trees on the west and east side of the highway for each element and plant part taken at the same sampling date.

made up only 0.03 to 0.08 percent of the dry weight of plant tissue, too low to cause damage. Absorption of chloride was 10- to 24-fold higher than sodium in declining trees on the east side of the road. Leaves of injured trees contained from 0.67- to 1.18-percent chloride. Decline and death of the silver maples were attributed primarily to chloride toxicity rather than to sodium uptake or osmotic concentration of the soil solution. There was no damage to silver maples having leaf chloride contents under 0.18 percent; a 0.20-percent chloride concentration caused slight leaf scorch and that above 0.50 percent produced moderate leaf scorch, defoliation, and ultimate death.

It is possible that sodium had some minor influence on deterioration of silver maples because the concentration of sodium was much higher in damaged trees than in healthy ones. However, sodium does not appear to be highly responsible because moderate concentrations were sometimes recovered in tissue showing no salt damage. With the onset of death, it was noted that chloride and, in some cases, sodium were lost from the woody tissue. Therefore, tissue analysis of a dead or dying tree may fail to diagnose injury from deicing salt ions.

For detailed information, see Appendixes A and B.

WOODY BIOTA AS INFLUENCED BY TWO DEICING SALTS AT THREE LOCATIONS

This section summarizes the findings of controlled field investigations with 18 types of woody plants grown in three physiographic regions in Virginia as they were influenced by two commonly used deicing salts—sodium chloride and calcium chloride. Three categories of woody plants—(a) deciduous trees, (b) deciduous shrubs, and (c) evergreen trees and shrubs—with six species in each category were selected for this investigation. Salt treatments were applied uniformly over the soil around the plants at various intervals. During the first winter, sodium chloride was applied at rates of 1500, 3000, 6000, and 12,000 lb per acre; calcium chloride at rates of 1500, 8000, and 12,000 lb per acre (Table 2). A general layout of the experimental site at Warsaw is shown in Figure 2.

TABLE 2

SODIUM CHLORIDE AND CALCIUM CHLORIDE TREATMENTS APPLIED DURING THE WINTERS OF 1966-67, 1967-68, AND 1968-69

	TREATMENT (LB/ACRE)	DATE OF APPLICATION [a]		
NaCl:	1,500	1966-67	1967-68	1968-69
	3,000	1966-67	1967-68	1968-69
	6,000	1966-67	—	1968-69
	8,000	1966-67	—	—
	12,000	1966-67	—	—
$CaCl_2$:	1,500	1966-67	1967-68	1968-69
	3,000	—	1967-68	1968-69
	6,000	1966-67	—	1968-69

[a] Applied in several split applications during late December through early March to simulate frequent applications made by highway personnel.

Deciduous Trees

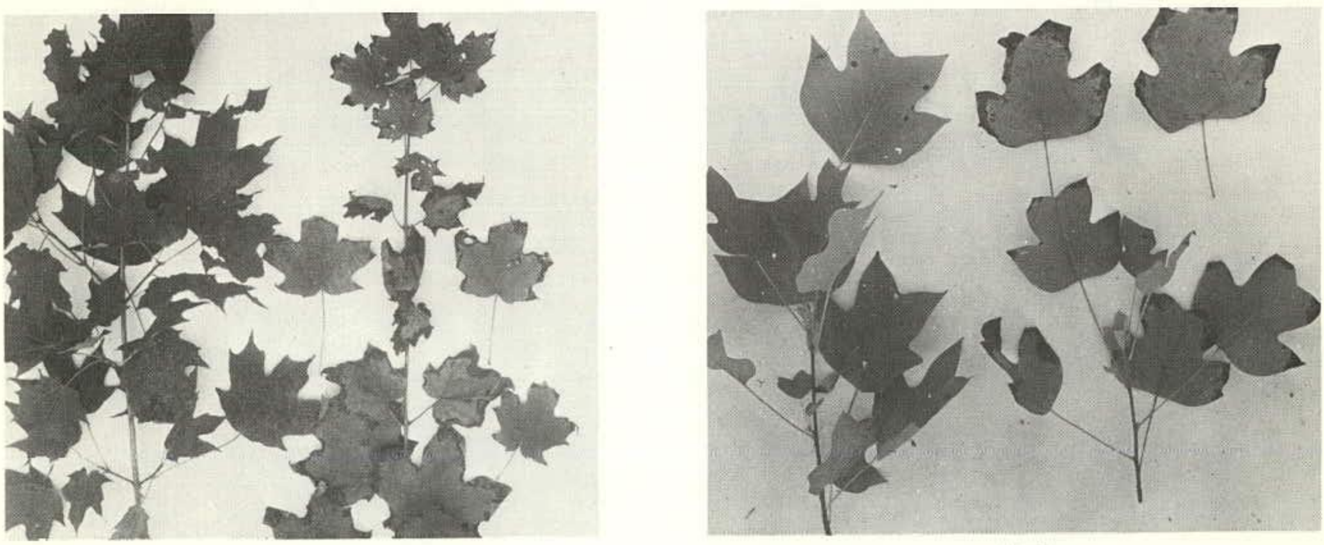
The symptoms of salt injury to deciduous trees, caused by their absorption of deicing salts, are shown in Figure 3. The salt tolerance ratings (or degree of injury to the trees) given in Table 3 are associated with the various rates of salt application made during the previous winter. Thornless honey locust trees were tolerant of both sodium chloride and calcium chloride and they remained healthy, even when exposed to the most severe salt treatments, during the 4-yr experiment. European white birch, sugar maple, and redbud were moderately tolerant, but high salt rates caused serious injuries from which many of the plants died during the summer following the first winter salt application. Green ash and tulip poplar species were severely injured by both salts at low application rates; the higher rates resulted in the deaths of most of these trees. Many of the green ash and tulip poplar trees died during July and August, which was the first summer following winter salt applications. Green ash was not reported for two areas because it was planted in the late fall to replace another species, and its survival was poor. The late planting and small size of the trees when treated with salt may have contributed to the salt susceptibility of green ash.

Application of sodium chloride and calcium chloride increased the chloride uptake in leaves and stems significantly for all deciduous trees during all years. In June 1967, chloride content in leaves after applications of salts at various rates the previous winter, shows marked increase (Table 4). Honey locust, which was salt-tolerant, absorbed the least chloride; tulip poplar and sugar maple absorbed the most chloride—up to 85-fold more than trees without salt treatment. Chlorides in stems and leaves of trees of various ages increased as more salt was applied until leaves became severely scorched; thereafter chloride concentrations declined. The reason for the decline is not understood; it is perhaps associated with leaching losses from injured tissue coupled with less absorption because of injured roots. At given rates of application, chloride uptake from calcium chloride was higher than from sodium chloride (Tables 4 and 5). This occurred because there is more chloride per pound in calcium chloride than in sodium chloride.

Chloride uptake and accumulation in leaves and stems varies with (a) amount of salt applied, (b) leaching losses through soils or runoff, (c) the plant species, and (d) age of the trees. Three years after their planting, salt-treated trees had lower chloride content than the small young trees the first year, except for the tulip poplar species, which had high chloride concentrations in both small and large trees (Tables 4 and 5). When averaging all salt treatments, the salt-susceptible tulip poplar absorbed about ten times more chlorides than honey locust, which is salt-tolerant. In order to establish the chloride concentration toxic to plants, one must consider the individual plant species, its age, soil fertility, and several other factors.

Sodium absorption was low; apparently sodium had only minor, if any, influence on the decline and death of trees treated with the deicing salts. Applying sodium salts increased the uptake, but the amounts absorbed were low, especially in the older trees (Table 5). During the first year

Figure 2. A general view of the experimental site at Warsaw, Va.



(b) (a)

Figure 3. Healthy leaves (left) are compared to those (right) showing symptoms of deicing salt injuries in the (a) tulip poplar and the (b) sugar maple.

TABLE 3

SALT TOLERANCE OF WOODY BIOTA BASED ON AVERAGE RATINGS FOR ALL RATES OF APPLICATION OF TWO DEICING SALTS *

WOODY BIOTA	MAY 1967		AUGUST 1968		
	BLACKSBURG	WARSAW	BLACKSBURG	WARSAW	ORANGE
Deciduous trees:					
Green ash (Fraxinus pennsylvanica)	—	3.6c	—	3.6c	3.6c
Sugar maple (Acer saccharum)	3.5c †	2.9b	3.8c	2.6b	2.5b
White birch (Betula pendula)	3.0b	3.0b	2.7b	2.7b	1.7a
Thornless honey locust (Gleditsia triacanthos inermis)	1.8a	1.6a	2.1a	2.2a	1.8a
Tulip poplar (Liriodendron tulipifera)	4.5c	4.0d	5.3d	4.2d	4.0c
Redbud (Cercis canadensis)	3.9d	3.0b	4.1c	2.9b	2.6b
Deciduous shrubs:					
Tartarian honeysuckle (Lonicera tartarica)	2.1a	2.4b	2.0a	2.4a	1.6a
Spring glory forsythia (Forsythia intermedia spectabilis)	2.8b	2.7b	3.3b	3.3b	1.4a
Spirea (Spirea Vanhouttei)	4.0d	3.5d	4.1c	4.1c	2.2b
Amur privet (Ligustrum amurense)	1.9a	2.1a	2.0a	2.1a	1.4a
Red-flowered weigela (Weigela Eva Rathke)	3.6c	3.0c	3.8bc	3.3b	1.7a
Rose (Rosa multiflora)	4.1d	3.6d	4.1c	3.5c	2.6c
Evergreen trees and shrubs:					
Creeping juniper (Juniperus horizontalis plumosa)	3.1b	2.6b	—	2.8b	—
Pfitzer juniper (Juniperus chinensis pfitzeriana)	2.3a	1.9a	2.0a	2.0a	—
Adam's needle (Yucca filamentosa)	—	3.0c	—	1.8a	—
White pine (Pinus strobus)	3.2b	3.3d	3.1b	3.7c	—
Norway spruce (Picea abies)	3.5b	3.6de	4.0c	4.7d	—
Canadian hemlock (Tsuga canadensis)	4.5c	3.7e	5.2d	4.9d	—

* Salt-tolerance ratings of the species were based on a numeral scale as follows: 1, healthy; 2, slight leaf scorching; 3, moderate leaf scorching and slight defoliation; 4 severe leaf scorching, moderate defoliation, and minor limb dieback; and 5, severe defoliation, extreme limb deterioration, and plant death. The ratings were made for the deicing salts applied at various rates (Table 2) that caused variable injury to the plant biota.
† Values within each species group for any location of year having different letters differ significantly.

TABLE 4

CHLORIDE AND SODIUM CONTENTS IN LEAVES OF DECIDUOUS TREES (WARSAW, VA., JUNE 1967)

SPECIES	CHECK	SALT TREATMENT [a] NaCl (LB/ACRE) 1,500	3,000	6,000	8,000	12,000	$CaCl_2$ (LB/ACRE) 1,500	6,000
		Chloride (% dry weight)						
Sugar maple	0.015	0.057	0.101	0.240	0.184	0.100	0.088	0.118
White birch	0.010	0.389	0.566	0.415	0.213	— [b]	0.137	0.367
Thornless honey locust	0.016	0.028	0.064	0.151	0.078	0.162	0.024	0.057
Tulip poplar	0.007	0.295	0.614	0.467 [c]	— [b]	— [b]	0.640	— [b]
Redbud	0.006	0.005	0.036	0.141	— [b]	— [b]	0.001	0.130
		Sodium (% dry weight)						
Sugar maple	0.012	0.026	0.056	0.120	0.124	— [b]	0.018	0.014
White birch	0.022	0.388	0.856	0.440	— [b]	0.820	0.016	0.022
Thornless honey locust	0.018	0.019	0.031	0.098	— [b]	0.054	0.016	0.013
Tulip poplar	0.030	0.015	0.040	0.013 [c]	— [b]	— [b]	0.017	— [b]
Redbud	0.018	0.023	0.022	0.033	0.033 [c]	0.039	0.018	0.015

[a] Salts were applied during the previous winter (see Table 2).
[b] All trees in all replications died.
[c] Live trees in only one replication.

after planting the trees, sodium absorption from the rock salt applications by white birch was consistently high (Table 4), but this did not occur in the same species two years later (Table 5).

Use of calcium chloride increased the uptake of calcium (Table 5), but this did not have adverse effects. Tulip poplar leaves were often twice as high in calcium as other deciduous trees.

Sodium and chloride uptake generally increased with the amounts of these ions in the soil, but this varied with species. The degree of salt injury to woody biota was allied with the chloride in leaves, but this relationship varied with species; such relationships with sodium were poor. Leaves were usually higher in sodium and chloride content than were stems.

Uptake of ions, especially chloride, from deicing salts occurred during the winter months, even though tops were dormant. Woody tissues showed increased salt ions in late winter before foliage appeared in spring. This supports the contention that roots function at lower temperatures than do tops; also, roots under massive snow cover encounter relatively mild winter temperatures sufficiently high to allow nutrient and ion absorption.

TABLE 5

CHLORIDE, SODIUM, AND CALCIUM CONTENTS IN DECIDUOUS TREE LEAVES (WARSAW, VA., AUGUST 1969)

		SALT TREATMENT (LB/ACRE)			
		1967-68 AND 1968-69		1968-69	
SPECIES	CHECK	NaCl 3,000	$CaCl_2$ 3,000	NaCl 6,000	$CaCl_2$ 6,000
		Chloride (% dry weight)			
Green ash	0.049	0.060	0.096	0.091	0.129
Sugar maple	0.031	0.134	0.231	0.387	0.185
White birch	0.060	0.100	0.075	0.118	0.133
Honey locust	0.093	0.115	0.148	0.114	0.125
Tulip poplar	0.162	1.564	1.918	1.424	1.987
Redbud	0.061	0.190	0.178	0.207	0.196
		Sodium (% dry weight)			
Green ash	0.006	0.006	0.010	0.012	0.004
Sugar maple	0.004	0.056	0.007	0.013	0.010
White birch	0.008	0.004	0.009	0.004	0.008
Honey locust	0.011	0.011	0.005	0.004	0.005
Tulip poplar	0.005	0.019	0.012	0.017	0.011
Redbud	0.002	0.005	0.007	0.005	0.011
		Calcium (% dry weight)			
Green ash	0.44	0.34	0.47	0.31	0.48
Sugar maple	0.65	0.40	0.63	0.58	0.73
White birch	0.53	0.52	0.55	0.51	0.79
Honey locust	0.51	0.50	0.50	0.58	0.57
Tulip poplar	1.02	0.77	1.21	1.00	1.13
Redbud	0.60	0.64	0.89	0.76	0.95

Deciduous Shrubs

Salt-tolerance ratings for six deciduous shrubs show that privet and honeysuckle survived even the heaviest applications of deicing salts and showed little or no dead wood and no visible symptoms of leaf burn (Table 3). Spirea and rose were severely damaged or killed as deicing salt applications increased from low to high amounts per acre. Symptoms of injury to spirea were complete leaf drop and dead woody tissue. Forsythia and weigela had intermediate salt tolerance, but with the highest applications of deicing salts they were damaged and killed. The rating values showed less salt injury for the location at Orange, Va., compared with the other two areas. These differences in plant ratings may well be an expression of salinity-fertility interaction because of the infertility of the Nason soil.

The salt tolerance of shrubs increased with age or size of plants, and a given rate of deicing salt application caused more injury to small plants than to large plants. This is attributed to the high absorption rate of chloride and sodium by small (young) plants as compared to older deciduous shrubs (Tables 6 and 7). Even low amounts of deicing salts (1500 lb per acre of sodium or calcium chlorides) caused sharp increases in chloride and sodium contents in leaves of all the small (young) deciduous shrubs (planted in spring 1966, treated with deicing salts the oncoming winter, with leaf analyses made the next June, Table 6). With sodium chloride applied at 3 tons per acre, the leaves of honeysuckle, forsythia, and weigela had more than 2 percent chloride and the sodium uptake averaged nearly 1 percent of the dry weight (Table 6). Thus, it appears that damage to these young shrubs was caused by the combined effect of sodium and chloride, with chloride being of primary importance. In contrast, older shrubs from the same site had chloride contents in their leaves of low to medium magnitude while sodium influence was nearly nonexistent (Table 7). Also, after applying 600 lb per acre of either of the two deicing salts, young shrubs (one year after planting) were killed, but the older deciduous shrubs (two years after planting) survived.

The data given in Table 7 suggest that the large, older deciduous shrubs were damaged or killed because of chlorides, whose contents were shown to be rather high in leaves. The older and larger plants of honeysuckle were low in chloride and not injured by deicing salts, even at the high rate of 6000 lb per acre. Privet absorbed considerable amounts of chloride but showed no injuries. Spirea leaves were high in chloride; rose and weigela had medium amounts, while forsythia was low in chloride; but all of these shrubs showed severe injuries that were allied with chloride absorption. Again, the leaves were much higher in chlorides than the stems.

Chloride uptake as shown by leaf analyses increased as salt applications increased, but uptake amounts varied with age of shrubs and species. Sodium uptake was not allied with rates of application of deicing salts, except for young plants when such relationships were fair. The rates of applying deicing salts had direct effects on increasing salt ions in the soil and absorption by plants. These relationships were much better with chloride than sodium ions. The highest concentration of chloride and sodium ions in leaves occurred when the chloride and sodium contents in the soil were about 3 and 4 milliequivalents (meq) per 100 g of

TABLE 6

CHLORIDE AND SODIUM CONTENTS IN LEAVES OF DECIDUOUS SHRUBS (WARSAW, VA., JUNE 1967)[a]

		SALT TREATMENT						
		NaCl (LB/ACRE)					$CaCl_2$ (LB/ACRE)	
SPECIES	CHECK	1,500	3,000	6,000	8,000	12,000	1,500	6,000
		Chloride (% dry weight)						
Honeysuckle	0.007	0.480	1.005	2.329	1.08[c]	0.739	0.090	0.946
Forsythia	0.154	0.389	0.842	2.242	1.434[c]	1.020[c]	0.869	2.011
Spirea	0.130	1.030	1.684	—[b]	—[b]	—[b]	1.074	—[b]
Privet	0.110	0.286	0.495	1.590	0.714	1.015	0.322	1.019
Weigela	0.069	1.608	1.706	2.050	1.736[c]	1.980	1.208	1.646
		Sodium (% dry weight)						
Honeysuckle	0.009	0.295	0.553	0.899	0.754[c]	0.945[b]	0.014	0.018
Forsythia	0.017	0.398	0.678	0.878	—[b]	0.800[c]	0.015	0.028
Spirea	0.010	0.180	0.530	—[b]	—[b]	—[b]	0.006	—[b]
Privet	0.008	0.228	0.666	1.079	0.486	0.687	0.009	0.015
Weigela	0.014	0.668	0.802	1.173	0.440[c]	0.908	0.014	0.010

[a] The salts applied during winter 1966-67 are given in Table 2.
[b] All plants in all replications died.
[c] Live plants in only one replication.

TABLE 7

CHLORIDE, SODIUM, AND CALCIUM CONTENTS IN LEAVES OF SHRUBS (WARSAW, VA., AUGUST 1969)

		SALT TREATMENT (LB/ACRE)			
		1967-68 AND 1968-69		1968-69	
SPECIES	CHECK	NaCl 3,000	$CaCl_2$ 3,000	NaCl 6,000	$CaCl_2$ 6,000
	Chloride (% dry weight)				
Honeysuckle	0.023	0.036	0.064	0.054	0.074
Forsythia	0.071	0.080	0.076	0.079	0.086
Spirea	0.197	0.788	0.926	0.663	0.895
Privet	0.199	0.205	0.493	0.288	0.453
Weigela	0.168	0.299	0.431	0.322	0.501
Rose	0.268	0.451	0.543	0.339	0.638
	Sodium (% dry weight)				
Honeysuckle	0.007	0.004	0.010	0.004	0.003
Forsythia	0.002	0.003	0.003	0.003	0.004
Spirea	0.007	0.008	0.009	0.014	0.010
Privet	0.009	0.017	0.007	0.034	0.008
Weigela	0.002	0.002	0.002	0.005	0.006
Rose	0.003	0.020	0.002	0.002	0.001
	Calcium (% dry weight)				
Honeysuckle	0.88	0.77	1.03	0.67	0.89
Forsythia	0.53	0.45	0.77	0.46	0.88
Spirea	0.81	0.67	1.25	0.45	1.29
Privet	0.68	0.44	0.84	0.45	0.76
Weigela	0.62	0.53	0.67	0.43	0.67
Rose	1.01	1.13	1.10	1.01	0.80

soil, respectively. When these ions occurred in larger amounts in the soil, the salt content of leaves tended to decline. This decline was attributed to plant injury from salt intake and subsequent leaching of salts from injured plant tissues. The high osmotic pressure in the soil solution also could have damaged and restricted root volume, which could account for less salt ion uptake.

The application of 3000 lb per acre of sodium chloride in split applications during January and February affected the chloride content of the stems of shrubs as early as March, and the first spring leaves also contained high amounts of chloride, resulting from applying deicing salts the previous winter. Thus, salt ion absorption during winter shows that roots are active in ion uptake. Seasonal changes in the percent of chlorides present in leaves varied greatly among the species.

At a given rate of application for the deicing salts, the responses of shrubs were similar, but chloride uptake was higher for calcium chloride than for sodium chloride (Table 7). Calcium chloride caused consistent increases in calcium content of leaves, except for the rose; calcium increases were large for spirea. These increases in calcium content of leaves were probably beneficial.

Evergreen Trees and Shrubs

Evergreens can be divided into two groups: three salt-tolerant and three salt-sensitive plants (Table 3). The salt-tolerant group includes Pfitzer juniper, creeping juniper, and Adam's needle. White pine, Norway spruce, and Canadian hemlock were very sensitive to injury from deicing salts; during the first winter, even the lowest rates of applying deicing salts seriously injured and frequently killed these less tolerant species. The three salt-sensitive evergreens were severely injured by the low salt rates (1500 lb per acre) and did not survive the first summer, yet the salt-tolerant group remained healthy. Pfitzer juniper and Adam's needle even survived the highest rates of deicing salts (6 tons per acre). Because of poor establishment at the Blacksburg location, Adam's needle was not included in the experiment and creeping juniper was excluded the second year. The degree of injury to the individual species varied with the type of salt. At 3-ton rates of these salts, calcium chloride caused more injury to white pine, while sodium chloride caused more injury to hemlock.

Figure 4 shows results of application of 1500 lb per acre of sodium chloride per year, which killed the three salt-sensitive evergreens. Figure 5 shows that heavy applications of deicing salts killed all evergreens except Pfitzer juniper and Adam's needle. These two evergreens lived even when grass and all other vegetation was killed.

Plant tissue analyses showed that the chloride content in all tissues increased significantly with increased rates of application of either deicing salt (Table 8). However, the percent of chloride accumulation in the tissues varied with the species of evergreens. The plants most severely injured by salts (white pine, Norway spruce, and hemlock) generally absorbed the most chloride ions. These three susceptible evergreens absorbed seven to fifteen times more chloride when treated with deicing salts than when grown in the absence of salt.

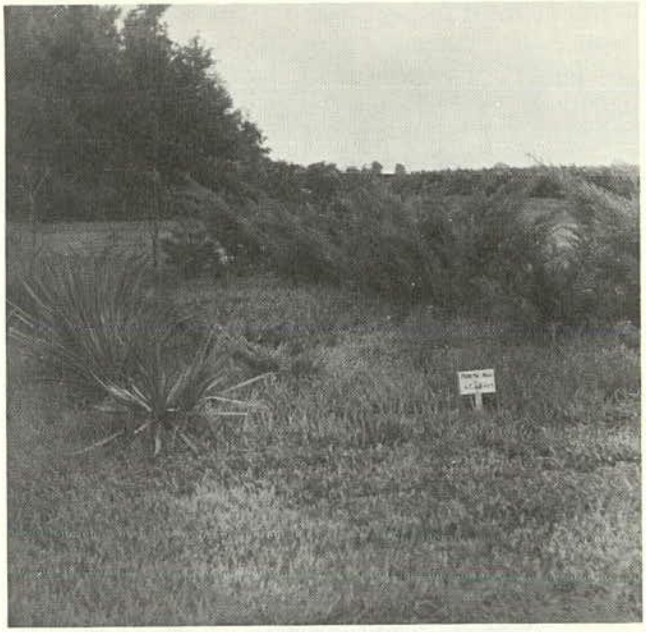


Figure 4. Of the evergreen plantings, only the hardy Adam's needle and juniper survived sodium chloride applications of 1,500 lb per acre for three successive years.

Figure 5. Although 6,000 lb per acre of deicing salts were applied to this planting, the Adam's needle and juniper remained vigorus and healthy. Note that grass growth became severely retarded with high rate of application.

Sodium absorption was much lower than for chloride (Table 8). It appears that injury cannot be associated with sodium because the sodium contents in tissues were similar for the control plants (no deicing salts) and rates of sodium chloride application.

Other analyses also show higher levels of chloride than sodium in plant tissues resulting from applying deicing salts. White pine, Norway spruce, and hemlock had tissues consistently high in chlorides at the various sampling dates. Calcium chloride, which did not supply sodium, caused severe injuries to the salt-susceptible evergreens, thus injuries are attributed primarily to the chlorides in deicing salts.

The chloride absorption of evergreens after applications of 1500 lb per acre of sodium chloride during two successive winters is shown in Figure 6. The amount of chlorides absorbed by the junipers was low and declined very sharply a year after the application. As compared with trees having no salt treatments (Fig. 6), the white pine and Norway spruce chloride levels were high and remained high. These two evergreens were severely injured by deicing salts. It is important to note that the salt-tolerant junipers had the highest chloride levels in March which then declined during the rest of the year. Conversely, for the white pine and Norway spruce the chloride concentrations in their tissues increased during the summer, and values remained high during fall and winter a year after the salts application (Fig. 6). Thus, susceptible evergreens absorbed large amounts of chlorides over prolonged periods of time, opposite behavior from that of the tolerant species.

Data similar to the sodium chloride deicing salt applications were obtained for sodium absorption (Fig. 7). The sodium chloride applications caused increases in sodium uptake, but the contents in plant tissues were low. The salt-tolerant junipers absorbed low amounts of sodium, most of which was absorbed during spring; during the later summer and winter seasons the sodium content was similar to that found in trees without deicing salt treatment. White pine, Canadian hemlock, and Norway spruce were very susceptible to injury from deicing salts, but only Norway spruce absorbed substantially more sodium from sodium chloride than the other evergreens (Fig. 7). The sodium concentrations in other evergreens were considered too low to be harmful. Thus, chloride and sodium together may cause Norway spruce to decline, but injury in other evergreens having low salt tolerance was caused primarily by chlorides. The evergreens showing little injury from deicing salts absorbed much less chloride than those susceptible to salt injury. For additional information, refer to Appendixes C, D, E, and F.

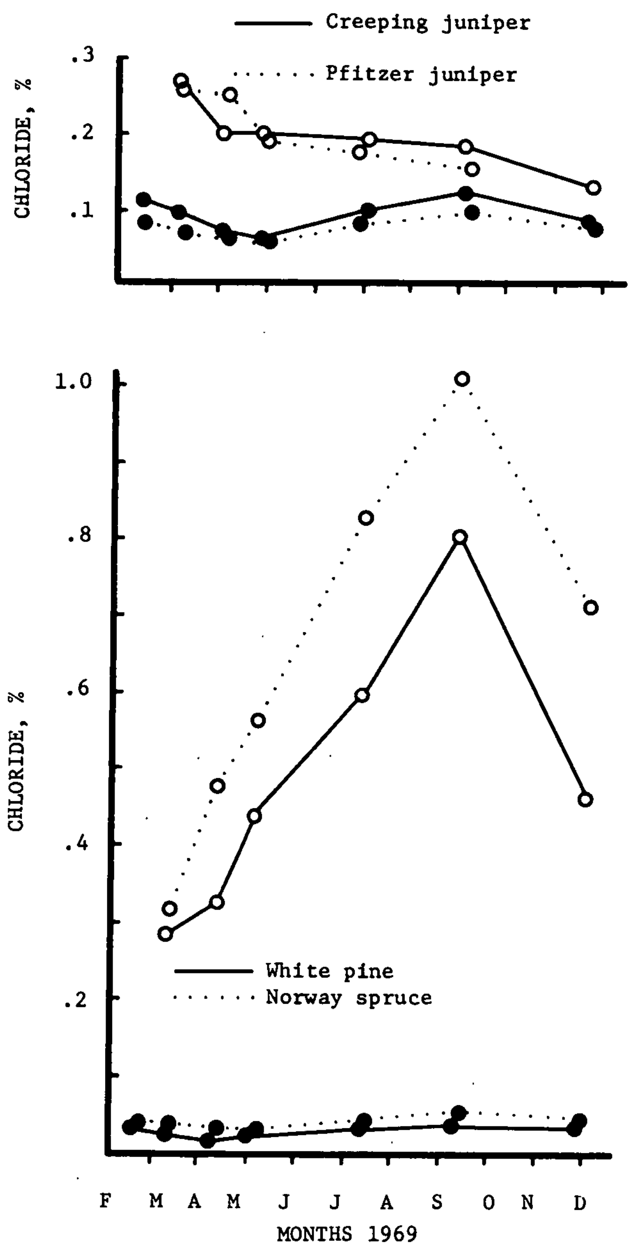


Figure 6. Chloride absorption (% dry weight) for various evergreen shrubs and trees during the 1969 season. In each graph, the upper set of lines indicates sodium chloride was applied during the 1967–68 and 1968–69 winter months at the rate of 1,500 lb per acre each winter. The solid circles refer to the same plants but which were without deicing salt treatment.

TRANSPIRATION AND PHOTOSYNTHESIS OF TREES

Various soluble salts provide elements essential for plant growth, but excessive amounts of most salts are injurious. A common plant response to excessive salt concentration is a general reduction in growth; however, plants differ greatly in their tolerance to large amounts of salts. At a given rate of sodium chloride, some plants show a stimulation of growth while other species die.

The physiological basis for the pronounced differences to salt tolerance in different plant species is not known, and very little is known about the effects of salt on plant metabolism (*2*). Two possible effects on plants from excessive available salts are a decrease in the rate of photosynthesis per unit leaf area and decreased utilization of

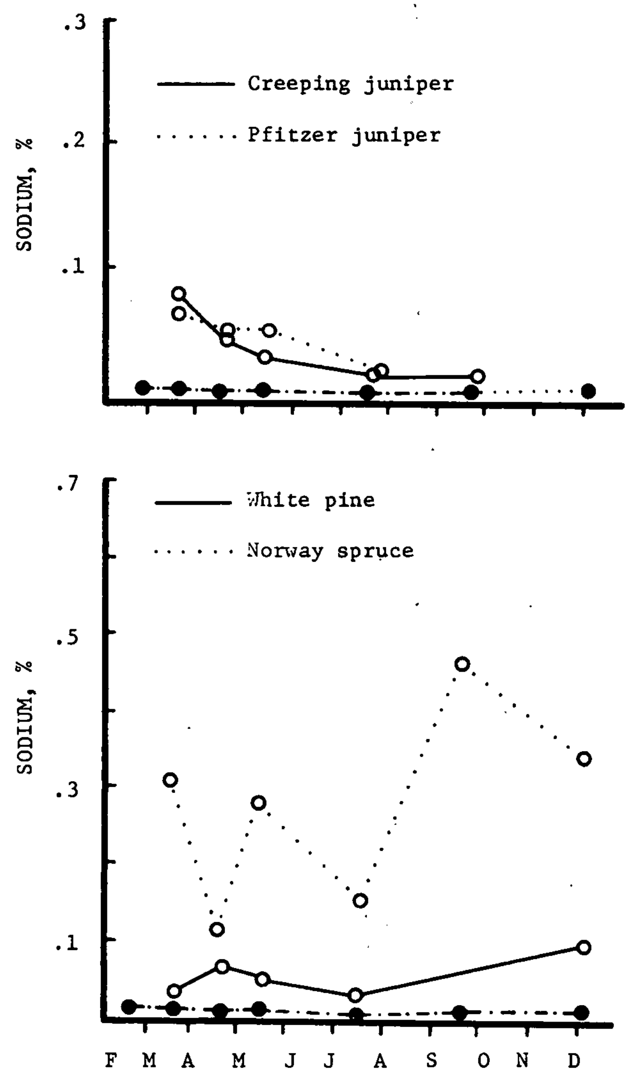


Figure 7. Sodium absorption (% dry weight) for various evergreen shrubs and trees during the 1969 season. In each graph, the upper set of lines indicates sodium chloride was applied during the 1967–68 and 1968–69 winter months at the rate of 1,500 lb per acre each winter. The solid circles refer to the same plants but which were without deicing salt treatment.

TABLE 8

CHLORIDE AND SODIUM CONTENTS IN FOLIAGE OF SHRUBS AND EVERGREEN TREES (WARSAW, VA., AUGUST 1968)

SPECIES	CHECK	SALT TREATMENT (LB/ACRE) 1967–68 AND 1968–69 NaCl 1,500	NaCl 3,000	CaCl$_2$ 1,500	1968–69 CaCl$_2$ 3,000	1968–69 NaCl 3,000
		Chloride (% dry weight)				
Creeping juniper	0.09	0.19	0.28	0.20	0.22	0.22
Pfitzer juniper	0.07	0.12	0.16	0.15	0.15	0.13
Adam's needle	0.12	0.42	0.96	0.50	0.18	0.21
White pine	0.04	0.55	0.51	0.41	0.62	0.50
Norway spruce	0.04	—[a]	0.29	—[a]	0.29	0.46
Canadian hemlock	0.04	—[a]	—[a]	—[a]	0.43	0.31[b]
		Sodium (% dry weight)				
Creeping juniper	0.004	0.057	0.098	0.004	0.024	0.068
Pfitzer juniper	0.006	0.013	0.019	0.006	0.003	0.024
Adam's needle	0.004	0.149	0.410	0.012	0.003	0.116
White pine	0.005	0.028	0.091	0.004	0.057	0.003
Norway spruce	0.003	—[a]	0.110	—[a]	0.011	0.205
Canadian hemlock	0.006	—[a]	—[a]	—[a]	0.010	0.170[b]

[a] All plants in all replications died.
[b] Live plants in only one replication.

photosynthates. Also, excessive amounts of salt may reduce respiration.

In a greenhouse experiment, three tree species were grown with the two deicing salts sodium chloride and calcium chloride as well as potassium chloride at osmotic pressures (O.P.) of ¼, ½, 1, and 2 atm. The leaf growth of redbud and honey locust showed stimulated growth for all salt treatments. Even the 2-atm concentrations of the three salts did not suppress growth. Conversely, leaf growth of sugar maple was suppressed by as little as ¼-atm O.P. of the salts.

Water transpiration per hour showed no differences for redbud and sugar maple between the control and the range of osmotic pressures for sodium and calcium chloride.

The rate of photosynthesis for sugar maple trees was suppressed as the osmotic pressure of sodium and calcium chloride solutions was increased (Table 9). However, the redbud rate of photosynthesis per unit leaf area tended to decline only with the highest osmotic pressures. The data suggest that tree species readily injured by deicing salts may encounter reduced growth because of suppression of photosynthesis. See Appendix G for details.

TABLE 9

EFFECT OF THE OSMOTIC PRESSURE OF TWO SALT SOLUTIONS ON RATE OF PHOTOSYNTHESIS (mg $CO_2/dm^2/hr$)

SPECIES	SALT	OSMOTIC PRESSURES OF SALT SOLUTIONS 0 ATM	¼ ATM	½ ATM	1 ATM	2 ATM
Sugar maple	NaCl	8.9	8.9	7.4	7.4	7.5
	CaCl$_2$	8.9	8.4	10.9	6.7	7.4
Redbud	NaCl	17.2	15.7	12.1	13.0	16.4
	CaCl$_2$	17.2	19.3	18.3	16.7	13.5

GRASSES INFLUENCED BY DEICING SALTS AND OTHER IONS EFFECTS

Applying sodium chloride at various rates to a sod of Kentucky 31 fescue showed sharp increases in both chloride and sodium in leaves for three samplings in late fall during a field experiment at Blacksburg (Table 10). Chloride and sodium increased with increased rates of sodium chloride application, but the chloride content in leaves, averaged for all treatments and samplings, was more than twice as high

TABLE 10

EFFECT OF SODIUM CHLORIDE TREATMENT ON THE CONTENTS OF SODIUM AND CHLORIDE IN KENTUCKY 31 FESCUE TOPS

NaCl TREATMENT (TONS/ ACRE)	AVERAGE CONTENT IN CUTTINGS (% DRY WEIGHT) SODIUM OCT. 24	SODIUM NOV. 4	SODIUM NOV. 18	CHLORIDE OCT. 24	CHLORIDE NOV. 4	CHLORIDE NOV. 18
0.00	0.07	0.07	0.02	0.93	1.34	0.97
0.25	0.47	0.42	0.31	1.60	1.66	1.46
0.50	0.82	0.59	0.59	2.38	1.94	1.57
1.00	1.58	1.16	1.08	3.04	2.90	2.06
2.00	2.00	2.10	1.58	4.12	3.76	2.59
4.00	3.20	3.20	2.68	5.33	5.55	4.16

[a] Applied in October and in November 1966. The grass had been seeded in spring 1966 and herbage was sampled during early autumn 1966.

as that of sodium. Note that sodium made up as much as 3.2 percent of the dry matter, and chloride content was as high as 5.55 percent. These high contents may be associated with the cool temperatures, slow growth, and low yields during fall.

In a field experiment near Warsaw, Va., sodium chloride depressed the yield of all four grasses investigated (Table 11). Increasing rates of sodium chloride were followed by a decrease in the yield of each grass. Grasses suffering reductions in yields from the most severe to the least severe were Kentucky bluegrass, bromegrass, red fescue, and Kentucky 31 fescue, respectively. Nitrogen fertilizer reduced the yield depressions caused by sodium chloride. With 50 lb of nitrogen per acre, Kentucky 31 fescue maintained a good ground cover even when the deicing salt sodium chloride was applied at 4 and 6 tons per acre.

Applying sodium chloride during winter months significantly increased the sodium and chloride contents and reduced the yields during the next season for all grasses (Table 11). However, the content of sodium in all four grasses was very small compared with that of chloride and probably was too low to cause physiological disturbances. Thus, injury to the grasses is attributed to high chloride absorption and accumulation in tissues. Kentucky 31 fescue tissues contained higher amounts of chloride than the other species. Apparently Kentucky 31 can tolerate higher amounts of chloride than other grasses.

Additional greenhouse research on the same grasses showed that 1000 ppm sodium chloride increased the top and root weight for Kentucky 31 fescue and Kentucky bluegrass at a high fertility and decreased the yield at the low fertility (Table 12). The higher rates of sodium chloride caused a reduction in the yield of top growth of all grasses at both fertility levels. However, the reduction in yield of Kentucky 31 fescue was less than that for red fescue and Kentucky bluegrass. Under high fertility, the reduction in yield with 4 tons of sodium chloride per acre was only 8 to 10 percent for Kentucky 31 fescue, while it was 30 to 50 percent for other grasses. Generally, the reduction in yield was more apparent for tops than for roots. Leaf tip burns were more noticeable for Kentucky bluegrass and red fescue than for Kentucky 31 fescue at all rates of sodium chloride application.

In another field experiment with Kentucky 31 fescue, increased rates of potassium decreased the uptake of sodium. Thus sodium uptake by grasses may be minimized by increasing the availability of soil potassium. Higher rates of nitrogen increased absorption and concentration of sodium and chloride in grass tissues. Nitrogen and potassium together caused increases in absorption of chloride and sodium, but to a lesser extent than for only nitrogen. There was little or no change in calcium and magnesium contents of grass because of rock salt applications.

The complementary effect of sodium and chloride ions on growth was studied in another experiment using corn seedlings as indicator plants. Phosphate and nitrate salts, separately or in combination with each other and with deicing salts, gave significantly higher yields of corn than all other treatments. Sodium chloride caused severe injury to the plants, such as burning the tips and margins of leaves and giving them a scorched appearance. Addition of sulfate as sodium sulfate improved the vigor of the plants to some extent but did not significantly decrease salt injury. However, phosphate alone or as a mixture of phosphate and nitrate in sodium, calcium, or potassium salts decreased sodium chloride injury significantly and also increased the vigor of plants. These results indicate that the deleterious effects of deicing compounds on vegetation along highways can be reduced by maintaining a good soil fertility program on roadside plantings.

Sulfate, phosphate, and nitrate ions applied as sodium salts decreased the uptake of chloride; they did not decrease the uptake of sodium ions by corn seedlings. Phosphate ions were more effective in reducing chloride uptake than sulfate ions. Sulfate, phosphate, and nitrate ions applied as salts of calcium and potassium also decreased chloride and sodium uptake. Potassium salts, however, were more effective than calcium salts. These results indicate that the use of potassium phosphate with deicing salts may be effective in decreasing sodium and chloride uptake, thereby minimizing salt injury.

Potassium reduced the uptake of sodium by grasses.

TABLE 11

EFFECT OF SODIUM CHLORIDE AND NITROGEN ON THE YIELD AS WELL AS SODIUM AND CHLORIDE CONTENTS OF FOUR GRASSES[a]

	BROME GRASS			RED FESCUE			KENTUCKY BLUEGRASS			KENTUCKY 31 FESCUE		
NaCl+ N TREATMENT (LB/ACRE)	YIELD (G/ PLOT)	Na (% DRY WT)	Cl (% DRY WT)	YIELD (G/ PLOT)	Na (% DRY WT)	Cl (% DRY WT)	YIELD (G/ PLOT)	Na (% DRY WT)	Cl (% DRY WT)	YIELD (G/ PLOT)	Na (% DRY WT)	Cl (% DRY WT)
Check	460	0.01	0.45	401	0.01	0.41	312	0.01	0.35	478	0.02	0.80
Check+50	527	0.01	0.58	460	0.01	0.47	338	0.01	0.59	513	0.02	1.20
4,000	361	0.04	0.55	356	0.03	0.41	196	0.03	0.50	395	0.01	1.05
4,000+50	399	0.03	0.63	390	0.06	0.86	220	0.03	0.52	438	0.14	1.12
8,000	180	0.04	0.60	147	0.03	0.53	100	0.03	0.41	207	0.17	1.13
8,000+50	225	0.05	0.81	177	0.05	0.70	144	0.09	1.15	260	0.03	1.58
12,000	100	0.11	0.89	96	0.07	0.55	82	0.08	0.97	194	0.24	1.02
12,000+50	150	0.07	0.89	131	0.07	0.77	100	0.07	0.81	238	0.22	1.72

[a] The grasses were established in 1966 on a sandy loam soil near Warsaw, Va.; the sodium chloride was applied during 1967-68 winter months; ammonium nitrate was applied in Aprli 1968 and the grasses were harvested in June 1968.

Phosphate ions reduced chloride absorption. Potassium phosphate was more effective in retarding chloride uptake than calcium phosphate. Analysis showed an inverse relationship between chloride and phosphate content in tissues. Hence, high soil phosphates should reduce chloride absorption.

These investigations show that there was less rock salt damage to plants with certain fertilizer salt nutrients than when rock salt was applied alone. Ions of potassium and phosphates competed with and reduced plant uptake of sodium and chloride, thereby improving plant survival. Before using fertilizer with deicing salt, the effectiveness of salts as ice-melting agents, costs of the material, and polluting potentials would have to be considered and investigated.

Perhaps the most practical way to benefit from desirable fertilizer ions is to maintain a good soil fertility status along roadsides where deicing salts might accumulate and cause injury to various plant biota. See Appendixes G and I for details.

TABLE 12

YIELDS OF TOPS AND ROOTS OF THREE GRASSES AS INFLUENCED BY SODIUM CHLORIDE AND SOIL FERTILITY

	YIELD (G/PLOT)					
NaCl TREATMENT [a] (PPM)	KENTUCKY 31 FESCUE		RED FESCUE		KENTUCKY BLUEGRASS	
	TOPS	ROOTS	TOPS	ROOTS	TOPS	ROOTS
High fertility:						
Check	1.66	4.24	2.22	4.43	1.95	2.28
1,000	2.43	5.66	1.82	3.86	2.13	3.24
2,000	1.67	3.98	1.13	3.73	1.43	2.66
4,000	1.53	3.86	1.00	3.56	1.30	2.32
Low fertility:						
Check	0.72	3.39	0.52	1.06	0.44	1.81
1,000	0.62	2.00	0.80	1.69	0.42	1.06
2,000	0.49	1.96	0.33	1.95	0.22	1.25
4,000	0.48	2.75	0.34	2.89	0.21	2.78

[a] The salt solutions were applied during a 17-day period after which tops and roots were harvested.

MOVEMENT OF DEICING SALTS IN SOIL PROFILES

Data collected from a Vermont roadside during the first winter and on through the following growing season show that deicing salts move both horizontally and vertically from the border of the treated highway (Figs. A-1 and A-2). Sodium and chloride accumulations in soils increased sharply during a 3-yr period (Fig. A-1). Salt accumulation in soil on the east side was much higher than on the west side of the road, the latter of which received little drainage water. The increase in salt accumulation in the soil was associated with the deterioration of trees discussed earlier. Increasing salt accumulation in the soil was attributed to deterioration of physical properties of the soil as a result of leaching and deflocculation actions caused by absorption of large amounts of deicing salt over a period of years. Due to increased permeability and less water movement through soils, salt concentrations could increase. Amount of rainfall and quantities of deicing salts would also influence salt accumulation in soil.

The highest concentration of sodium and chloride salt ions and osmotic concentrations in soils occurred 3 ft from the edge of the pavement on the eastern (drainage) side of the highway (Fig. A-2). The amount of salt ions in the soil declined sharply with distance from the highway, especially on the east side.

The distribution of chloride at various depths in the soil profile shows sharp changes at various dates on the east side of the road, where trees were injured or killed (Fig. A-3). These high salt concentrations were found to a distance 15 ft from the highway and showed their influence on the root environment of trees because injured trees were found at this distance from the road. Sodium concentrations followed patterns similar to those for chlorides with sampling dates; hence these findings support the conclusion that sodium and chloride ions increase in soils receiving drainage waters from highways carrying deicing salts. Also, a strong trend is for such contamination to increase with time. Sodium and chloride ion concentrations were always lower in the soil on the west side of the road and did not change appreciably with depth. High concentrations of sodium and chloride occurred in the soil profile to a depth of 18 in. or more on the east side of the road even during winter. These salts moved into the profile during winter, which is contrary to the common opinion that deicing salts are carried off in drainage water over frozen soils. Salts "percolate" into soil horizons when frozen, thereby encouraging root absorption and build-up of ions during winter. These findings support the idea of a yearly buildup of harmful ions in woody biota tissue, thereby having accumulative and delayed detrimental effects on plants.

In a Virginia experiment, after two deicing salts had been applied at various rates in a number of split applications on a Sassafras sandy loam planting during the 1966-67 winter, large amounts of salt ions were found in the surface 10 in. of soil the next June. The amounts of chloride and sodium in the soil were directly related to the quantity of salt applied (Table 13). The highest values for chloride and sodium were 5.51 and 6.34 milliequivalents (meq) per 100 g of soil, respectively. In practical terms, a value of 1 meq of chloride per 100 g of soil is approximately 700 lb of chloride per acre. Of the total amount of deicing salts applied the previous winter, 54 to 92 percent chloride remained in the soil by the next June; for sodium, 44 to 57 percent remained in the upper 10 in. of the soil. Chloride absorption by woody biota increased as chloride amounts in the soil increased, although uptake varied with species. High sodium accumulations in the soil caused only small sodium increases in stems and leaves of woody plants.

To establish rates and patterns of ion movement, deicing salt treatments were applied in experiments designed to study the salt tolerance of woody biota. Investigations included studying a soil in each of the three physiographic regions in Virginia. The patterns of ion accumulation and disappearance for the three soils were similar; hence, only data for the Sassafras soil near Warsaw are given.

After a period of several months from application of the

TABLE 13

PERCENTAGE OF CHLORIDE AND SODIUM RECOVERY FROM THE 1- TO 10-IN. HORIZON IN SASSAFRAS SOIL (WARSAW, VA., JUNE 1967)[a]

	TREATMENT (LB/ACRE)	Cl MEQ/ 100 G SOIL	Cl % RECOVERY	Na MEQ/ 100 G SOIL	Na % RECOVERY
Check:	0	0.03	—	0.02	—
NaCl:	1,500	0.72	54	0.60	44
	2,000	1.47	56	1.15	44
	6,000	3.92	76	2.98	57
	8,000	5.26	76	3.83	55
	12,000	6.34	61	5.51	53
$CaCl_2$:	1,500	0.95	67	0.04	—
	6,000	5.06	92	0.07	—

[a] The data are averages of four replications. Percent recovery is the percentage of chloride or sodium that was recovered from the soil after various rates of deicing salts had been applied the previous winter.

deicing salts and under natural rainfall conditions, high concentrations of deicing salt ions occurred in upper soil profiles and were especially high in the surface ½ in. of the soil. The high surface concentrations are attributed to the surface applications and surface water evaporation. Salt ion concentrations sharply reduced with soil depth when either rock salt or calcium chloride was applied.

It was found that chemical analyses of water extracts for either of the cations (sodium or calcium) or the anion (chloride) or electrical conductance would be used to diagnose movement and concentration of ions in various soil horizons. Specific electrical conductance measured the combined effects of the deicing salt ions in soils. The water extracts from various soil horizons show that deicing salt ions move readily with infiltrating water to the lower soil profile depths. Application of deicing salts during the winter caused substantial increases in the respective salt ions beyond 40-in. soil depths.

Leaching of ions from deicing salts through the soil profile, which reestablishes normal soil conditions, was rapid for both of the deicing salts. For example, rock salt or calcium chloride was applied to a plot at the rate of 6000 lb per acre during the 1967-68 winter. Chloride concentrations in water extracts from soil profile layers were very high (particularly so for calcium chloride because it has more chloride per pound than does rock salt) during the 1968 growing season. However, chloride leached away rapidly. By 1969 the chloride concentrations contained in water extracts from various depths were very low and by 1970 the chloride contents were no higher than for soils not treated with deicing salts. Chloride tended to leach out of soils faster when used as calcium chloride rather than sodium chloride. This may be attributed to favorable effects on soil structure by calcium.

The pattern of sodium disappearance was similar to chloride, but somewhat slower. Two years after applying rock salt, the soil solutions from various soil horizons were considered normal for growing any plant biota. The low amount of sodium contained in the water extracts one year after application suggests that the soil would have been suitable for culture.

After calcium chloride had been applied at 6000 pounds per acre during the 1967-68 winter, the calcium in water extracts to a 20-in. depth in the soil increased sharply by June 1968. By 1969 the calcium status in various layers of the soil profile was similar to that for soils without deicing salt. A considerable portion of the calcium applied as calcium chloride became attached to the colloidal exchange complex and did not appear in water extracts.

Under natural rainfall conditions in Virginia, both sodium chloride and calcium chloride were effectively leached out of the soil profile in a 3-yr period. Chemical changes, such as pH depression and the exchange of salt ions for plant nutrients in the soil, that are brought about by the presence of deicing salts tend to reach new equilibriums once the salts were leached (see Appendixes A and J for details).

SALT SPRAY AND ROOT UPTAKE OF SALT IONS

A careful examination of the site at Vermont (Appendixes A and B) reveals that deicing salt sprays are of no consequence to the decline of silver maples. There was no visible damage to trees on the west side of the highway or those on both sides of the highway at either the top or far bottom of the slope. Therefore, neither proximity to the highway or prevailing winds could be responsible for the observed decline of the silver maples. Dead trees were found at the bottom of the slope where drainage accumulation was maximum, while no visible decline occurred at the top of the slope or at locations along the roadside having little or no drainage waters from roads where deicing salts had been applied. However, some tree deterioration was noticed midway down the slope on the east side of the road where highway drainage occurred. Damage to the trees, therefore, appears to have resulted from the root uptake of ions from the soil rather than from the salt spray.

Deciduous trees were sprayed heavily and repeatedly in Virginia experiments with the deicing salt sodium chloride. In experiments at the Warsaw location, deciduous trees and shrubs and evergreen trees and shrubs were sprayed on four occasions during the winter with saturated sodium chloride–water solutions. The trees were sprayed until droplets began to form on woody tissues of deciduous plants and on needles of evergreens. Injury ratings of all species the subsequent spring showed no perceptible damage or abnormal leaf and stem development. Leaf tissues from all sprayed plant biota were analyzed for sodium and chloride concentrations. There was no evidence of increased sodium or chloride contents as a result of the four winter sprayings. With this experiment root absorption of deicing salts by various trees and shrubs was kept low since spraying ceased when droplets began to form. Although foliar absorption of ions is a known fact, there was not adequate foliar absorption of ions from the deicing salt sprays to cause growth abnormalities of the plant biota investigated.

In another experiment at Blacksburg, pines were repeatedly sprayed during winter with saturated solutions of sodium chloride. The salt drippings from some trees, caused by heavy spraying and washing by rains, were permitted to reach and infiltrate the soil to be absorbed by the trees' roots. Plastic troughs were constructed for other trees to drain away all drippings and leachings of salt from foliage to avoid any root absorption. Although the pines were excessively sprayed to obtain a whitish foliage, there was no evidence of damage except for a somewhat dulled foliage color for some trees. It is likely that salt ion intake by top growth during the winter is nil in deciduous plants and minimal in evergreens because of low respiratory and other physiological activity of leaves.

ROADSIDE PLANTINGS

Various woody species were planted at different distances from a main highway in both Minnesota and Illinois to study the influence of deicing salts applied by highway departments. Soils, sampled at various depths and distances from the road, and tissues from the woody plants were analyzed for salt ions. The results were variable and inconclusive.

CHAPTER THREE

CONCLUSIONS AND APPLICATIONS

It is well known that snow and ice on roadways and walkways cause severe delays in traffic and are potential hazards to individuals. Snow and ice removal from highways and streets by mechanical means supplemented by deicing salts is especially necessary for packed snow and ice. There is at present no economical substitute for deicing salts. It is known that liberal uses of deicing salts are often harmful to plant biota, though harmful effects to animal biota and humans in the humid regions of the United States are not now serious because of the kind of ions in deicing salts and the fact that they leach readily.

The question of alternatives to using deicing salts is an important and timely one. One alternative is to completely avoid any environmental contamination and injurious effects from deicing salts by discontinuing their use. This approach would result in traffic delays, property damage from hazardous driving conditions, and increase in injuries and deaths among humans caused by automobile accidents. Excessive delays in traffic causing motors to operate over longer periods of time would add sharply to the gaseous phase of environmental pollution if use of deicing salts is prohibited. A second alternative is to use salts in excessive amounts to assure bare pavement during winter regardless of any detrimental effects. A third alternative is to practice moderate use of deicing salts, to keep traffic moving during snow and ice conditions at reduced speeds and thus minimize both injuries and deaths to humans and the detrimental effects of the deicing salts on roadside vegetation and water supplies.

The adoption and practicing of the last approach depend a great deal on educating highway and street maintenance personnel in the most desirable storage, handling, and application methods for deicing salts. Flexibility must be allowed, as exact quantities and times of applying deicing salts cannot be legislated; this depends on prevailing weather conditions.

Carelessness in applying excessive amounts of deicing salts, such as nonuniform distribution, uncontrolled application, poor placement, and spreading beyond pavements, leads to serious pollution and added costs. Maintenance personnel should be aware of the potentially harmful effects of deicing salts on soils, plant biota, and water supplies whenever deicing salts are used. Promiscuity in applying deicing salts can pollute water supplies, impair their use for industrial purposes, and can eventually become injurious to animal biota. Fortunately, mammals have high salt tolerances because of efficient kidney systems which eliminate salt ions and other toxic substances.

Harmful Effects of Deicing Salts

The two commonly used deicing salts, calcium chloride and sodium chloride, are fortunate available choices because the ions in these salts are less harmful than some other salts with desirable melting properties. For example, the two ions in calcium chloride are essential mineral nutrients for all living things, both plant and animal. The components of rock salt, sodium and chloride, are essential for animal life although sodium is not an essential ion for plant biota. Sodium in small amounts stimulates many plant species, but in large accumulations it is harmful to plants. Chloride is needed only in small amounts by plants. Even low contents in plant tissue are potentially injurious and often lethal.

History of Deicing Salt Ions

Sodium chloride is a highly ionized salt, which means that its ions dissociate and are highly soluble in water. Chloride, an anion, is repelled by clay and organic colloids in soils because they also have negative charges. Thus, chloride flows freely in the water phase of soils and is readily dissipated by leaching, particularly in humid regions where rainfall is high.

On the other hand, various positively charged ions (such as potassium, calcium, magnesium, sodium) are attracted by negative charges of colloidal soil materials. However, because the large hydrated sodium ions (only one positive charge) are "weakly attached," most of the sodium remains in soil solution and leaches readily from soils. On the other hand, the small calcium ions (two positive charges) readily enter the base exchange complex, but excess amounts also leach away. The aluminum ions being very strongly attached to clay colloids in many soils in the humid region almost totally inhibit sodium and partially restrict calcium from entering the base exchange complex. In semi-humid areas, where soils are high in calcium and magnesium, the firm contact of these cations also inhibit sodium exchange, causing it to be vulnerable to leaching.

Soil data in this report show that large amounts of calcium, sodium, and chloride are present in soil solution after deicing salt applications. Chloride ions in soil water extracts are consistently higher than either calcium or sodium. A measure of either the cations, anions, or the electrical conductance shows a definite pattern of salt movement down through the soil profile. The speed with which the deicing salts are removed from soils depends on the amount that has been applied, the amount of rainfall, the length of time the soil is frozen, the size of the pore spaces, and the chemical properties of soils.

Deicing salts high in chlorides have other indirect effects on soils. The chlorides encourage the leaching of other cations (such as potassium, calcium, and magnesium) that are essential for plant growth and, in the presence of sodium, may cause clay particles to deflocculate. Sodium causes soils to become more dense and compacted; the smaller pore spaces inhibit aeration, water infiltration, and leaching of salts, making the soil a poor environment for plant growth.

Harmful Effects to Plant Biota

The very high solubility of sodium and chloride in soil solutions causes them to be readily available for root uptake. There is overwhelming evidence that the chloride ion is primarily responsible for toxic injuries to the plant species investigated in this research. In some situations, especially with young or small trees and shrubs, sodium may have caused interacting effects to augment injury and inhibit growth. Chloride was absorbed in much larger amounts than sodium by all grasses and trees investigated. Young trees generally absorbed more chloride than older ones, and the absorption of sodium by such young trees and shrubs was substantial as compared to near nil for most older tree species. Leaf tissues accumulated higher levels of chloride and sodium than the stem tissues. The chloride content in plant tissues varies sharply with seasons. Thus, when diagnosing salt injury, it is difficult to establish absolute values of toxic concentrations because amounts contained in plant tissues vary with age, species, kind of tissue, nutrient balance, seasons of sampling, and other factors.

Plant species vary in susceptibility to salt injury because some trees and shrubs absorb less chloride and sodium than others. Also, some tolerant species absorbed large amounts of sodium and chloride and were not injured, this was especially so with Kentucky 31 tall fescue.

Mechanisms causing deicing salt injury are not clearly understood. However, it is apparent that absorbed chloride ions are highly toxic to many plants. For salt ions other than chloride, the primary harmful effects are probably on the osmotic effects in soil solutions.

Soil–Plant–Time Interplay

Salts become injurious to plants when absorbed from soils by the plant roots. Sodium and chloride ion concentrations in plant tissues, especially those having low salt tolerance, are generally highly associated with the concentrations of the salt ions in the soil solutions and the length of time the plant roots are exposed to the solutions. However, deicing salt ion concentrations need not necessarily be high in soil solutions to cause severe toxic effects. Plant roots are efficient in absorbing soluble ions from low-concentration soil solutions to attain significant accumulations in plant tissues. Because roots spend respiratory energy in ion uptake, they absorb ions against concentration gradients (e.g., ion concentration becomes much higher in plant tissues than in soil solutions). Thus, low amounts of salt ions infiltrating soils year after year can cause high concentrations of ions to accumulate in plants. In woody species, ions from annual applications of deicing salts can accumulate in tissues from year to year. Trees do not have adequate mechanisms to counteract salt ion accumulation in tissues. Rapid growth of plants would dilute the salt in tissues; however, salt usually depresses growth thereby causing further increases of salt accumulation in tissue. For salt-susceptible woody plants, a common sequence of events is increased salt ion concentrations in tissue, stunted growth, dropping leaves, dropping twigs, dying limbs, and finally plant death. The dropping of dead tissues is not an effective way of recovering from salt accumulation caused by year-to-year applications of deicing salts.

Winter Relationships

It has been erroneously believed that the application of deicing salts during the winter months is potentially harmless because they are soluble and are carried off in the flow of surface drainage waters over frozen soil surfaces. Although frozen conditions do encourage surface drainage, deicing salt ions do infiltrate frozen soils and do increase substantially in soil horizons. Also, many soils are protected by heavy snow cover and never freeze. Thus, salt ions from drainageways may enter soils during the winter months.

It has been assumed that roots, as well as tops, of deciduous and other trees are more or less dormant during the winter months. The data, in fact, showed substantial uptake of sodium and chloride ions during the winter months when top growth is dormant. Thus, although the top soil horizons may be frozen, temperatures in the lower horizons are high enough to encourage respiratory energy for salt ion uptake. This point was supported by tissue analysis of deciduous and evergreen trees and shrubs.

Spray Damage Confounded with Root Absorption

The relative importance of spray injury resulting from applying deicing salts along highways as compared with salt ions entering plants through roots is a complex problem. It is recognized that consistent salt sprays can and do kill top growth of plants as with naturally occurring salt sprays from salt waters or imposed salt spray situations along roadsides. However, the effects of salt sprays are never isolated from ion uptake by roots. Salt spray accumulations on plant surfaces drip to the substrate and then become available for root absorption. Because there is often very little snow under certain shrubby and evergreen plants, the spray drippings would readily enter the soil for root absorption. Thus spray injury is invariably associated with root uptake of salt ions. Because ions enter foliar tissues, it is possible that salt sprays augment ion concentration in tissues of evergreens. Damage from salt spray on dormant deciduous plants seems unlikely. During this project, deciduous and evergreen trees were sprayed repeatedly with sodium chloride solutions and no injury or any significant effects of salt ions on leaf tissue were observed.

The top portion of grasses growing along highways is usually dormant during the winter months. Salt spray on vegetation adjacent to highways would not damage grass top growth, but the deicing salt ions from sprays or drainage waters that enter soils along highways and streets could be lethal to grasses through root uptake.

Minimizing Injury from Deicing Salts

Major salt damage occurring to vegetation along highways is attributed to salt ions from drainage waters entering soils. Deicing salts in soil horizons were high on the side of the road receiving such drainage waters. Also, deicing salt ions present in soil horizons diminished with distance from the highway.

1. It is thus important to plan highways to minimize salt accumulation in soils from surface waters drained from highways treated with deicing salts. In some cases it may be desirable to construct paved channels to carry surface waters bearing deicing salts from highways during the winter months.

2. Woody plants should be planted as far away from pavements as possible so that at least part of the root system will be free of the salt-contaminated environment. A tree with half of its root system in a soil environment relatively free of deicing salts is less apt to be injured than one where all of the roots are in a salt-laden soil. However, that part of the plant in a salt environment is still apt to show severe scorching or death.

3. It is important to select plant species that are highly resistant to injury from deicing salt ions. The data herein show marked differenecs of trees, grasses, and shrubs in ion uptake and tolerance. This investigation determined salt tolerances of plant biota, as follows:

PLANT BIOTA	SALT TOLERANCE
Deciduous trees:	
Honey locust	Good
Redbud, sugar maple, white birch	Moderate
Tulip poplar, green ash	Poor
Deciduous shrubs:	
Honeysuckle, privet	Good
Weigela, forsythia	Moderate
Rose, spirea	Poor
Evergreen trees and shrubs:	
Creeping juniper, Adam's needle, Pfitzer juniper	Good
Norway spruce, white pine	Moderate
Hemlock	Poor
Temperate perennial grasses:	
Kentucky 31 tall fescue	Good
Bromegrass, red fescue	Moderate
Kentucky bluegrass	Poor

4. Deicing salts should be used judiciously; applications should be restricted to minimum amounts needed for ice and snow removal.

5. Fertile soils, especially those high in phosphate, will aid in reducing injury to plants from deicing salts.

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APPENDIX A

MOVEMENT AND DISTRIBUTION OF DEICING SALTS IN A VERGENNES SOIL

Highway salting practices have increased the concentrations of sodium and chloride and the specific conductance in a Vergennes soil located on the east side of US 7, 5 miles south of Shelburne, Vermont. This was manifested in an extensive silver maple decline on the east side of the road, whereas healthy trees were growing on the west side of the road where, due to the slope, drainage from the highway was limited.

Hutchinson and Olson (*3*) had determined that sodium and chloride contents in soils adjacent to salted highways were higher after deicing salts were applied. Salt effects were greatest at the edge of the road embankment and where salting had been practiced for the longest periods. In some instances, increases in the concentrations of sodium and chloride occurred at a distance of 60 ft from the highway. The sodium contents were usually raised higher than chlorides. The sodium concentrations at some sites were high enough to cause dispersion and poor drainage of the soil, and the sodium and chloride concentrations were rapidly approaching a point where they could be toxic to vegetation growing in the area.

Prior and Berthouex (*4*) found that the maximum concentrations of salt occurred at the soil surface and nearest the highway. Some salts moved more than 100 ft laterally from the highway, even when the topography was very gently sloped. However, after February the tendency for salt to move even 25 ft laterally appeared considerably reduced. Although there was some tendency for salts to move laterally away from the highway, the most prevalent movement was downward into the soil. As infiltration proceeded, salt concentrations were markedly lower at the surface. Generally, the salt concentrations in the subsoil decreased as depth increased. The salt ions were readily leached from the top several feet of soil, and the majority of the salts had disappeared by April. The salt concentrations continued to decrease gradually during the summer and reached low levels before salt applications were resumed the following winter. It was concluded that the soil salinity problem resulting from highway deicing with salts was minimal for the field conditions studied.

Holmes (*5*) reasoned that, because the ground was frozen during the period of salting, most of the salt probably dissolved in melting snow and ran off over the surface without reaching the plant root zones. Analysis of soil collected in the spring or summer from plots salted in the winter often revealed little or no increase in soluble salts above those of the check plots.

RESEARCH APPROACH

The purpose of this investigation was to determine the distribution and movement of deicing salt ions in a Vergennes soil bordering a highway at a site 5 miles south of Shelburne, Vermont, on US 7, and, if possible, to relate this to extensive silver maple decline in the area.

The soil bordering the highway is primarily a Vergennes clay, a moderately well-drained soil developed from micaceous glacial lacustrine clays (Glossoboralfic Normudalfs). Scattered pockets of Panton clay were also present. This soil belongs to the same soil catena as Vergennes clay but is poorly drained. Due to slope, highway runoff occurs primarily to the east side of the road. On this side of the highway is noticeable damage to and even death of numerous silver maples, while trees on the west side of the road are growing vigorously.

Soil samples were taken from both the east and west sides of the highway midway along the slope. The samples were collected on the dates shown in Figure A-1 at 3-ft intervals from the road and at 3-in. increments in depth. The samples were dried, ground, and extracted for one hour with a 2:1 ratio of distilled water to soil. The pH was determined by using a Beckman Zeromatic pH Meter and the samples were filtered on a Buchner funnel. The specific conductivity of the filtrate was determined on an Industrial Instruments conductivity bridge Model RC 16B2; chloride was determined by an Aminco-Cotlove Automatic Chloride Titrator; and sodium and calcium, by a Beckman DU Flame Spectrophotometer.

RESULTS AND DISCUSSION

Table A-1 gives data concerning the average sodium and chloride contents of the soil and the specific conductivity of the soil extracts. The specific conductivity on the east side of the road, where deterioration of silver maples was visible, averaged twice as high as that on the west side while the sodium and chloride contents were six and ten times higher on the east than on the west side of the road, respectively. The average content of calcium extracted was not appreciably different on the two sides of the road. This fact lends support to the hypothesis that trees growing in the soil on the east side of the highway would be susceptible to salt damage because they were growing in a medium containing a high salt content and therefore could take up more salt.

The specific conductivity and concentrations of sodium and chloride were always higher (Fig. A-1) on the east side of the highway when compared to those on the west side for all eight sampling dates. Although silver maple decline was observed for the 9-14-66 and 9-15-67 sampling dates, it does not appear that the small increases in salt content on the east side of the road could have produced the great differences observed between the trees located on the two sides of the highway. However, during this time period, soil samples were not collected in the wintertime. After this period, samples were collected in December and

April, and generally it was observed that the salt concentrations increased during the winter. This is logical because deicing salts are applied to the highway during this time period. From April through September, the salt content in the soil generally decreased, which is most likely a result of the leaching action of spring and summer rains.

The salt concentration in the soil increased over the period of years the study was conducted, with a large increase noted on the east side of the road during the 1967-68 winter period. This could have been a result of less water movement through the profile due to deterioration in the physical properties of the soil from the leaching action of

TABLE A-1

SOIL ANALYSIS TO DETERMINE AMOUNTS OF CHLORIDE, SODIUM, AND CALCIUM IN SAMPLES COLLECTED FROM THE 9- THROUGH 21-FT INTERVALS FROM THE HIGHWAY AND THE 0- TO 12-IN. DEPTH IN THE HORIZON AVERAGED FROM EIGHT SAMPLING DATES

ROADSIDE SAMPLED	SPECIFIC CONDUCTIVITY (μMHOS/CM)	CONTENT IN SOIL (PPM)		
		Cl	Na	Ca
East	1045.9	268.4	243.4	59.4
West	482.1	26.8	40.2	73.4

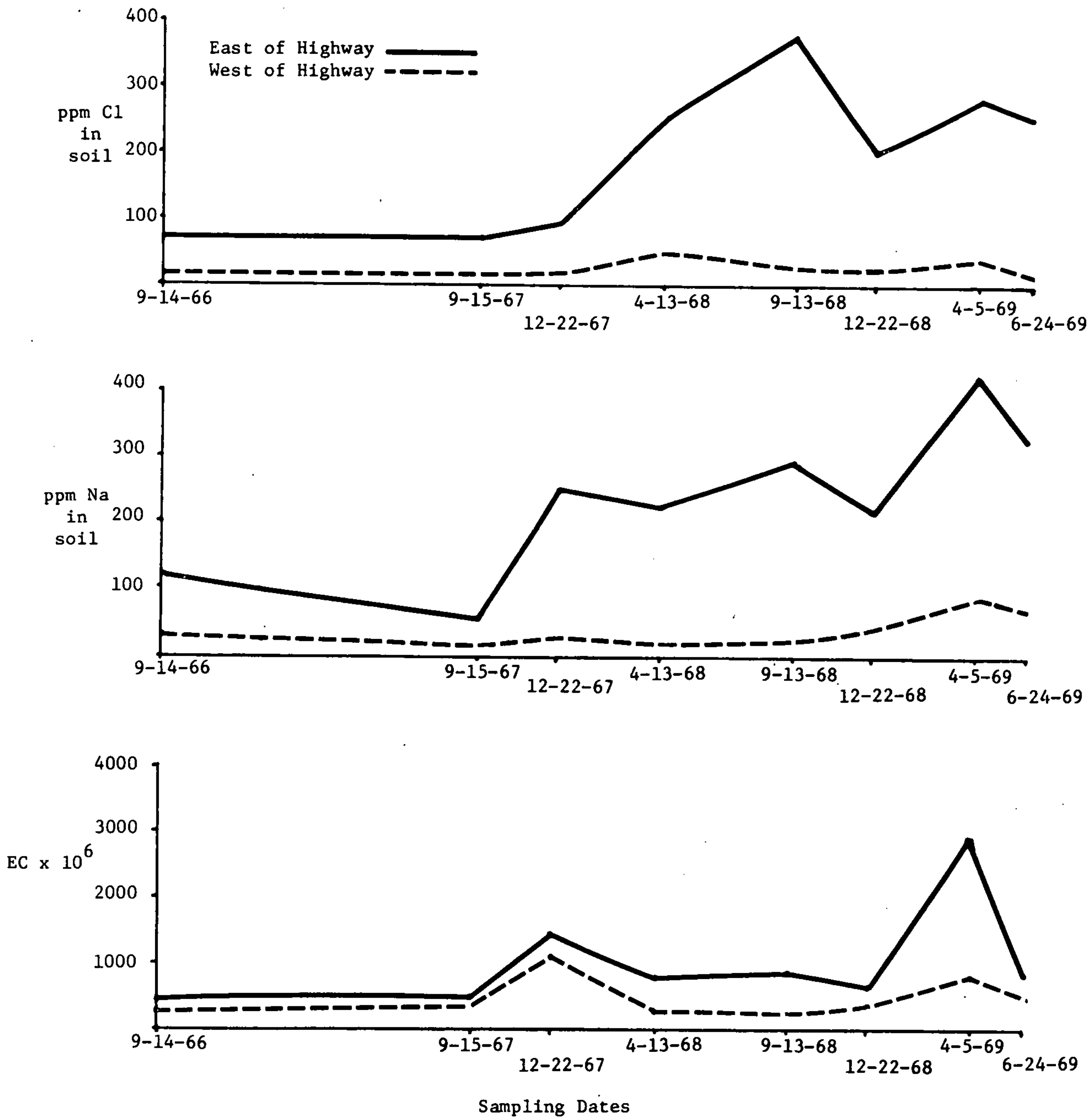

Figure A-1. Average chloride and sodium concentrations and specific conductance for soil samples collected over a distance of 9 to 21 ft from the highway and to a depth of 0 to 12 in. as affected over eight sampling dates.

large quantities of salt. Due to a decrease in soil permeability, the salt concentration in the soil would continue to increase and would not even decrease during the summertime. This could account for the high concentration of salt in the soil on the east side of the road for the 9-13-68 sampling period. In addition, the rainfall distribution and quantity of deicing salts used are factors to be considered.

Generally, the specific conductance correlated with the water-extractable sodium and chloride in the soil. The differences between the soil on the east and west sides of the highway in concentrations of sodium and chloride were larger than differences in specific conductivity measurements. Since rock salt is primarily sodium chloride, direct measurement of the sodium and chloride ions gives a better measure of the influence of deicing salts to soils bordering highways than does specific conductance. Conductivity measures the influence of the total number of ions present, whatever they may be.

The sodium ion may be adsorbed on the soil complex, replacing other cations. This appears to have occurred to some extent in the soil containing high concentrations of sodium, wherein pH values as high as 8.4 were observed,

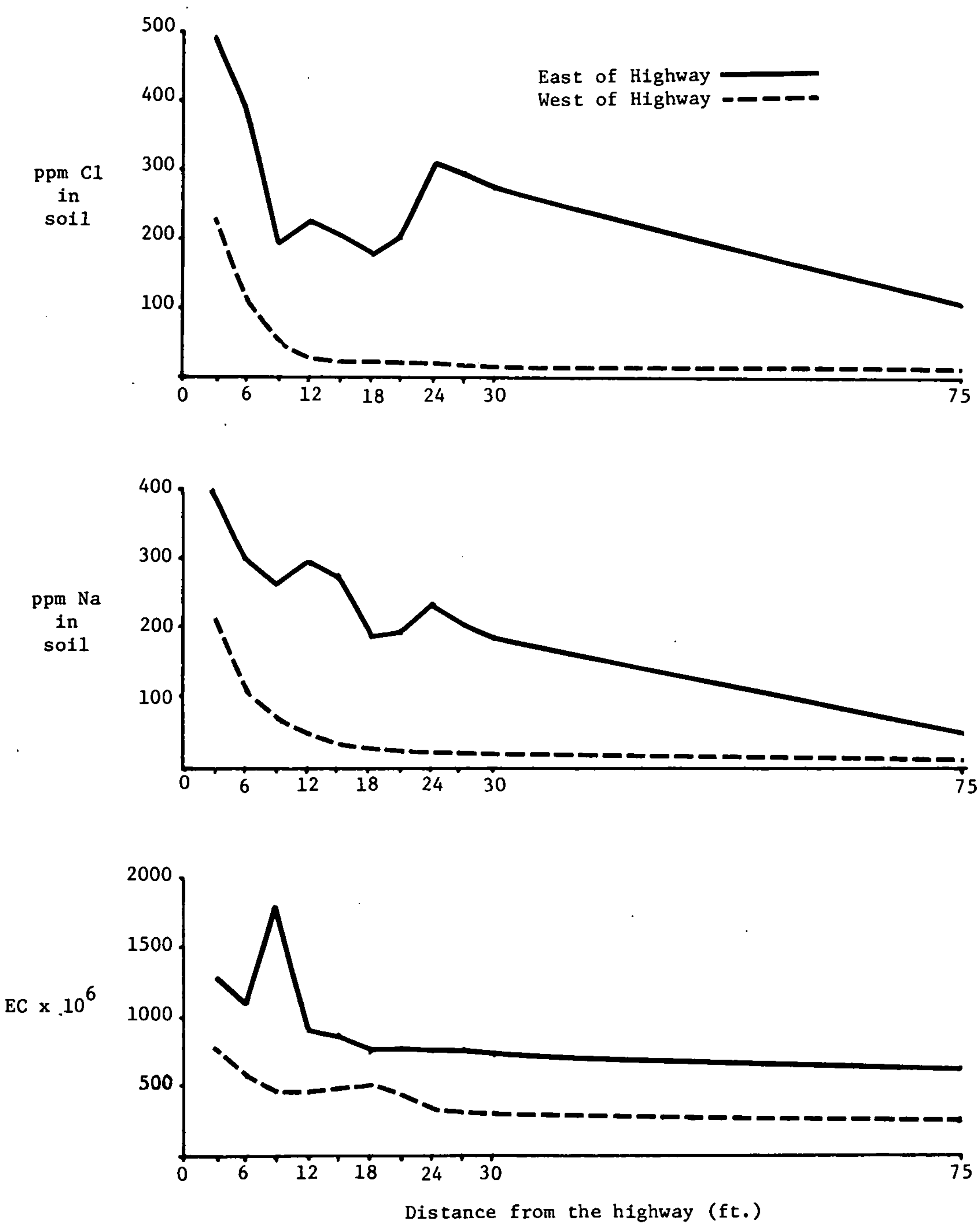

Figure A-2. Average chloride and sodium concentrations and specific conductance in soil sampled 0 to 12 in. in depth during eight sampling periods as affected by distance from the highway.

while the soil containing minimal amounts of sodium had a pH ranging between 5.4 and 6.6. The chloride anion, however, would not be adsorbed on the latter soil because it does not have much anion exchange capacity. However, due to the large amounts of water-extractable sodium and chloride and the similarity in their concentrations, it is suspected that the majority of these ions exist as an ionized salt in soil solution.

The largest salt concentration in the soil occurred 3 ft from the pavement on the east side of the highway for the 4-5-69 sampling date. Specific conductivity was 3,960 micromhos/cm (EC $\times 10^{-6}$) and the soil contents of sodium and chloride were 1,080 and 2,577 ppm, respectively. A specific conductance this large in a 2:1 water-to-soil extract is classified as moderately saline (*6*) and would restrict the growth of many plant species. The osmotic pressure caused by the salt in the soil system was about 1.5 atm. However, by the 6-24-69 sampling date, the amount of salt in the soil had diminished sharply and the osmotic effect at this date was less than 0.5 atm.

Although such concentrations of sodium and chloride in soil are large enough to cause injury to some trees (*7*), these amounts did not persist through the horizons or at further distances from the pavement. The amounts of salt were much lower in soil that contained most of the tree roots for all the sampling dates. Nevertheless, the decline of silver maples in areas so near the road seemed to be associated with chloride toxicity because there were high contents of sodium and chloride in damaged trees (see Appendix B). The large quantity of salt present in damaged trees and apparently low contents in soils containing many tree roots may have resulted from salt uptake during the winter when higher concentrations of salt may have existed than those reported for the early winter and spring sampling dates. On the other hand, trees may be removing salts from soil deeper within the soil profiles.

It should be pointed out that plants not subject to annual harvesting, such as trees, can accumulate salt within their tissues over a period of years and, thus, can become susceptible to salt injuries with time. This point of view was expressed by Hayward, Long, and Uhvits (*8*), and Monk and Peterson (*7*). They reported that the effect of saline substrates may be cumulative and over a period of years even low soil concentrations of salt may cause a slow but progressive decline of trees.

In general, the salt concentration in the soil decreases with increasing distance from the highway (Fig. A-2). This appears logical because salts are applied on pavements and the amount present should decrease with distance from the source of contamination. On the west side of the highway, increases in the amount of salt detected in the soil occurred to about 9 ft from the highway during all seasons of the year. This is probably caused by plowing operations and the occurrance of a highway ditch at this point. However, on the east side of the road, an increase in the salt content of the soil occurred beyond the 75-ft sampling distance from the highway. Great increases in concentrations of sodium, chloride, and specific conductance were noted to occur up to 30 ft from the edge of the pavement. This effect was most prominent during the winter and spring and decreased in the summer and fall. It was also observed that the differences in concentrations of sodium and chloride between the soil on the east and west sides of the highway were larger than differences for specific conductance.

The distribution of salts through a soil profile depends on the quantity and distribution of rainfall, soil properties, and amounts of salt applied to the soil surface. Because the climatic factors are similar on both sides of the road and the soil properties similar except for the changes imposed, the main variable is the amount of salt applied at the surface. This was observed to be dependent upon distance from the highway. The silver maple trees were growing at a distance of about 15 ft from the edge of the highway, and this distance was chosen to demonstrate the distribution of sodium and chloride through the soil profile at the eight sampling dates (Figs. A-3 and A-4). Similar patterns were evident at the remaining sampling distances.

Distributions of sodium and chloride through the profile during a given sampling period were similar. These ions therefore move together through the soil profile and these findings support the conclusion that a large quantity of the sodium and chloride ions exist as an ionized salt in soil solution. The levels of sodium and chloride throughout the soil profile on the west side of the highway were always lower than those on the east side of the road and did not change appreciably with depth or sampling date. The distribution of sodium and chloride in the soil profile on the east side of the highway generally showed surface accumulation during the winter and spring periods with a movement downward through the profile during the summer and fall. The gradual buildup of salts throughout the entire profile for the soil on the east side of the highway also suggests a deterioration in the physical characteristics of the soil preventing leaching.

It is interesting to note that high concentrations of sodium and chloride occurred to a depth of 18 in. or more in the soil profile on the east side of the road even during winter. It was evident that salts moved down into the profile during winter. This is contrary to the opinion that deicing salts carried in drainage water flow over frozen soil. Apparently salts are capable of percolation into the soil horizon when the ground is frozen. Stoeckeler and Weitzman (*9*) found almost normal infiltration in a forest soil frozen to a depth of 4 in. while corn and pasture areas showed almost no infiltration when frozen to a similar depth.

CONCLUSIONS

Highway salting practices have increased the concentrations of sodium and chloride and the specific conductance in the soil on the east side of the highway for the site examined. This was manifested in an extensive silver maple decline on the east side of the road, while healthy trees were growing on the west side of the road where a natural slope limited highway drainage.

The maximum concentrations of sodium and chloride were generally found at the soil surface and nearest the highway pavement. The concentrations of salt in the soil increased during the winter and then decreased during summer and early fall. Sodium and chloride ions entered the soil profile during winter and penetrated into deeper horizons as time progressed. Higher-than-normal concentrations of sodium and chloride were found to depths of 18 in. and distances of 75 ft from the pavement. As years progressed, the quantity of sodium and chloride increased throughout the entire soil profile. It is suspected that the passage of large quantities of salt through soil profiles cause

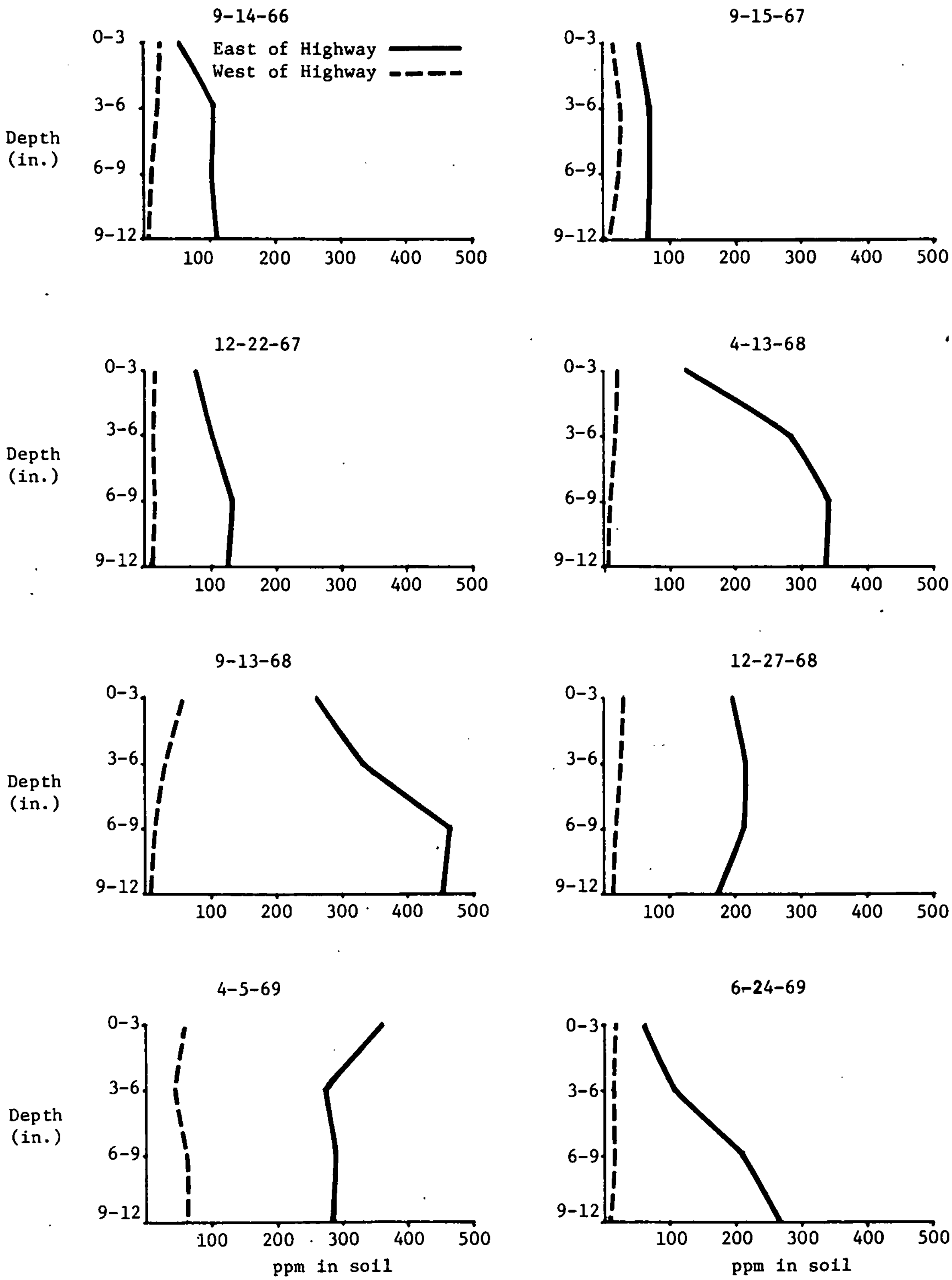

Figure A-3. Distribution of chloride in the soil profile for samples collected 15 ft from the edge of the highway on both sides of the road during eight sampling dates.

a deterioration of the physical properties of the soil, thereby causing a decrease in soil permeability.

During the winter season, the deicing salts move both horizontally and vertically from the highway border. The amount of salt ions present at any given distance and depth depends on (a) highway deicing practices, which include the kind and amount of salt used, time of application, as well as the snow removal procedures; (b) climate, which includes amount of precipitation, amount of snow cover, and temperature; (c) soil properties, which include slope, permeability, and salt retention capabilities; and apparently (d) the presence and absorption of these ions by tree roots.

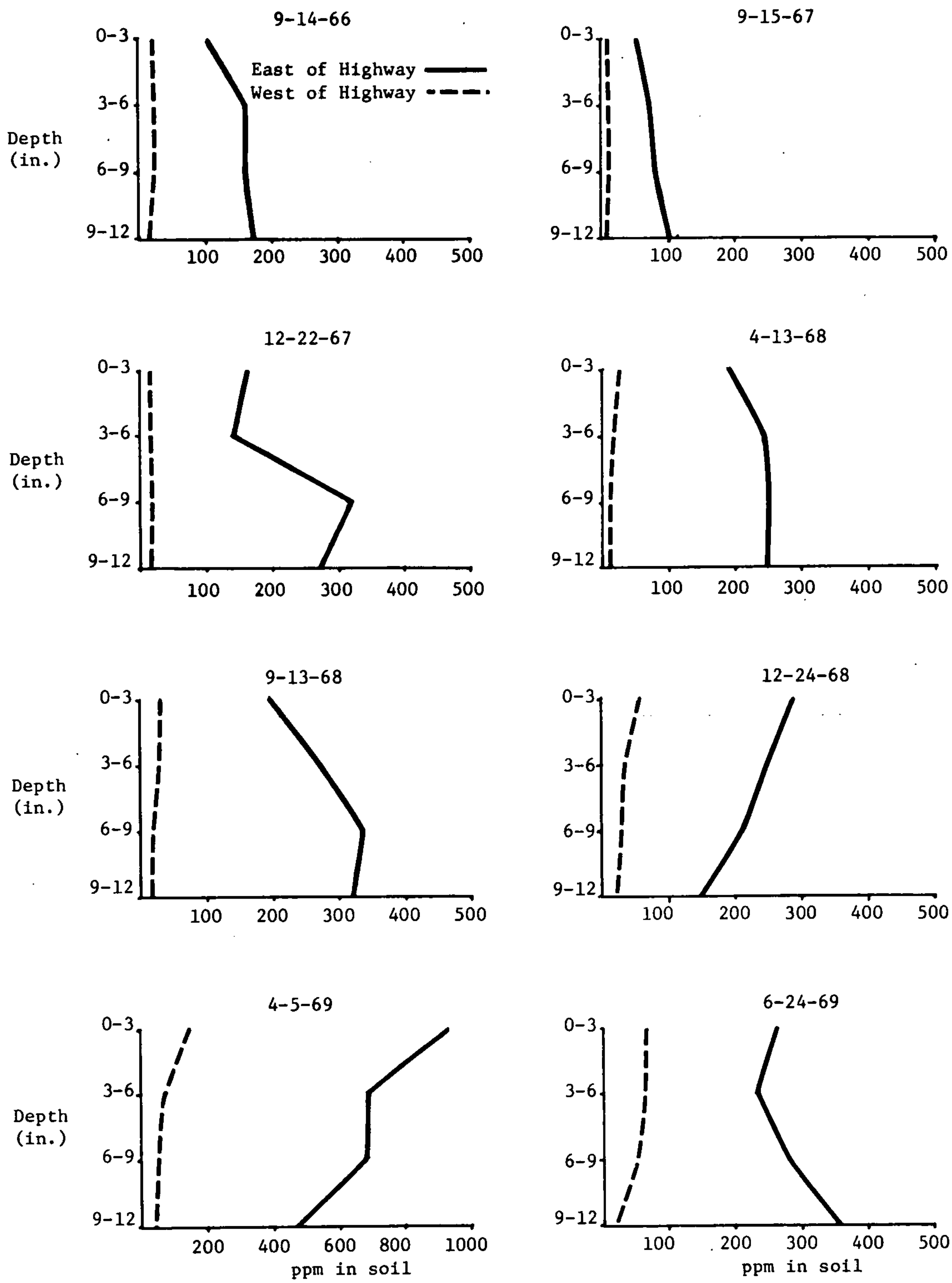

Figure A-4. Distribution of sodium in the soil profile for samples collected 15 ft from the edge of the highway on both sides of the road during eight sampling dates.

APPENDIX B

EFFECTS OF DEICING SALTS ON SILVER MAPLE TREES (Acer saccharinum)

While the use of sodium chloride and calcium chloride as efficient and economical means of deicing highways has increased, so has their rate of application. These chemicals are suspected of damaging roadside vegetation, which creates an unsightly condition in that the progressive signs of injury develop as a general growth reduction followed by leaf scorch and curling, leaf drop, stem dieback, and gradual decline in vigor ultimately resulting in death of the plants. Such unsightliness can decrease property value as well as serve as a poor advertisement for, and possibly retard, the highway beautification programs. Removal from old travelways of dead woody vegetation, which is a hazard to motorists, as well as replanting requirements increase the cost of highway maintenance programs.

French (*10*) reported salt injury symptoms to boulevard trees, especially American elm, after winter salt application to city streets. Injury to trees was observed predominantly at intersections or streets receiving heavy applications of deicing salts and was more obvious on the side of trees facing the street. The injured tissues were reported to contain above-normal amounts of sodium.

Lacasse and Rich (*11*) showed that maple decline in New Hampshire was limited to the immediate roadside and its drainage area and was apparently caused by severe salt injury. Higher-than-normal amounts of sodium were recovered in the leaves and twigs of damaged trees. Kotheimer, Rich, and Shortle (*12*) found that the chloride contents in sugar maples correlated significantly with damage ratings, and the quantities of chloride measured were several times higher than sodium, except in the cases of terminal decline.

Button and Peaslee (*13*) concluded that an increased exposure of trees to roadside drainage increased the deterioration of sugar maples in Connecticut. The damaged tissue contained higher concentrations of sodium and chloride and lower concentrations of calcium, magnesium, and potassium than healthy tissue. It was thought that the injury was due to the toxicity of a specific ion rather than to an osmotic effect, and chloride was suspected as being the toxic ion.

However, Holmes (*5*) reported that winter road salting probably does no great harm to trees in Massachusetts. No salt injury symptoms were observed on trees in runoff plots after 7 years of salt application to an adjacent road, although trees directly treated with consecutive weekly applications of salt did develop chlorotic foliage with necrotic margins, and ultimately some trees died. The damaged vegetation was found to contain higher concentrations of chloride in the tissues than untreated trees. This experiment was continued (*14*) and the findings supported the earlier conclusions. Sugar maples demonstrating little or no foliar injury contained a foliar chloride content of 0.05 to 0.6 percent whereas those with severe leaf scorch contained about 1 percent.

RESEARCH APPROACH

The purpose of this investigation was to determine the possible causative role of deicing salts in an extensive decline of silver maples in a highway environment 5 miles south of Shelburne, Vermont, on US 7. The site contained about 250 trees, which were primarily mature silver maples of a similar age, planted opposite each other about 15 ft from the edge of the highway. Due to slope, highway runoff occurred primarily to the east side of the road. Trees on the east side of the highway were noticeably damaged and many were dead while trees on the west side of the road were growing vigorously. This site, therefore, provided an excellent opportunity to determine the influence of deicing salts on silver maple growth and vigor in a natural highway environment. Damage ranging from the extreme of no vegetative damage to that of dead trees was visible in an area containing enough trees of the same species and age to study statistical significance of salt effects under the same environmental conditions, soil type, and highway practices.

Leaf and twig samples of the silver maple trees were collected from both sides of the highway on the dates given in Table B-1. Samples were dried and ground. Chloride was extracted with a 1:100 ratio of plant material and a mixture containing 0.1 N nitric acid and 10 percent glacial acetic acid. Chloride was determined by using an Aminco-Cotlove Automatic Chloride Titrator. A second portion of tissue was dry ashed and brought up to volume with 0.3 N nitric acid contained in a 100:1 ratio of solution to plant material. Amounts of sodium, potassium, and calcium were determined on a Beckman DU Flame Spectrophotometer; magnesium was determined on a Perkin-Elmer Model 303 Atomic Absorption Spectrophotometer; and phosphorus, on a Beckman Model B Spectrophotometer by the vanadomolybdophosphoric yellow color method using a wavelength of 470 mm. The chemical data was statistically analyzed by using the paired "*t*" test. Statistical comparisons were made between trees growing on the west side of the highway and and those growing opposite them on the east side of the road for each element and plant part taken at the same sampling date.

For the June sampling period, the trees were rated from 1 to 5, which corresponded to the extent of injury recognized as:

1. Healthy.
2. Slight leaf scorching.
3. Moderate leaf scorching, slight defoliation.

4. Severe leaf scorching, moderate defoliation, minor limb death.

5. Severe defoliation, extreme limb deterioration, or death.

RESULTS

The decline of silver maples from 1967 through 1969 at the site examined is shown in Figure B-1. The trees on the right side of the photographs are located on the east side of the highway and are damaged while healthy trees are

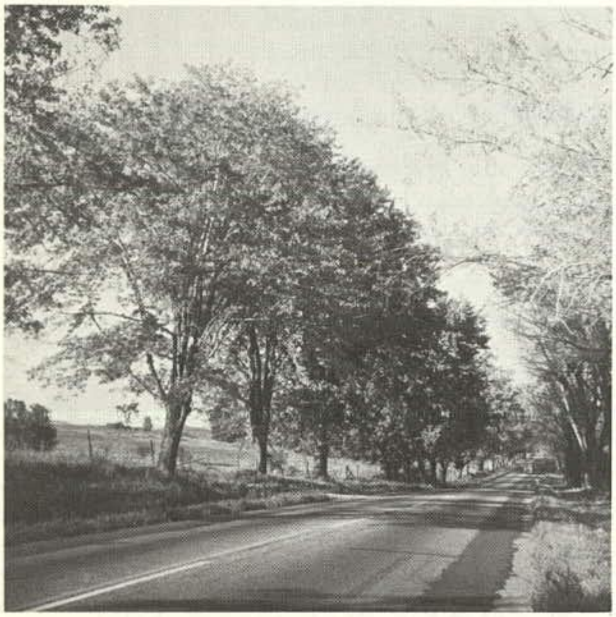

TABLE B-1

CHEMICAL ANALYSIS TO DETERMINE AMOUNTS OF CHLORIDE, PHOSPHORUS, SODIUM, POTASSIUM, CALCIUM, AND MAGNESIUM IN TISSUES OF SILVER MAPLES LOCATED ON US 7 SOUTH OF SHELBURNE, VERMONT, AVERAGED FROM SIX SAMPLING DATES

SAMPLING DATE	ROAD-SIDE SAM-PLED	PLANT PART	PRESENCE IN TISSUES (%) Cl	P	Na	K	Ca	Mg
9–14–66	West	Leaf	0.30	0.18	0.01	0.75	0.88	0.26
		Stem	0.18	0.13	0.01	0.48	1.60	0.15
	East	Leaf	0.83 [a]	0.19	0.04 [a]	1.18	1.08	0.24
		Stem	0.36 [b]	0.15	0.05 [a]	0.78	1.87	0.14
9–15–67	West	Leaf	0.26	0.24	0.01	0.91	0.84	0.33
		Stem	0.22	0.21	0.01	0.76	1.48	0.25
	East	Leaf	0.70 [a]	0.17	0.03 [a]	1.64 [b]	1.07 [b]	0.33
		Stem	0.94 [a]	0.24	0.05 [b]	1.15 [a]	1.38	0.20
6–20–68	West	Leaf	0.15	0.28	0.01	1.08	0.65	0.20
		Stem	0.07	0.10	0.02	0.46 [b]	0.96 [b]	0.07
	East	Leaf	0.67 [a]	0.30	0.03 [a]	1.49 [a]	0.78 [b]	0.22
		Stem	0.13 [a]	0.06	0.04 [b]	0.32	0.78	0.05
9–13–68	West	Leaf	0.32	0.21	0.00	1.12	1.19	0.26
		Stem	0.09	0.11	0.01	0.45 [b]	0.95	0.09
	East	Leaf	1.18 [a]	0.15	0.05 [b]	1.37	1.01	0.27
		Stem	0.19 [a]	0.08	0.02 [b]	0.31	0.86	0.06
4–5–69	West	Leaf	0.14	0.06	0.14	0.10	0.99	0.05
	East	Stem	0.20 [a]	0.06	0.16	0.19	0.90	0.04
6–24–69	West	Leaf	0.16	0.26	0.01	1.25	0.60	0.18
		Stem	0.11	0.14	0.01	0.58	1.00	0.08
	East	Leaf	0.83 [a]	0.28	0.08 [a]	1.50 [b]	0.72	0.19
		Stem	0.27 [a]	0.11	0.06 [a]	0.50	0.87	0.07

[a] Indicates significance at the 1-percent level.
[b] Indicates significance at the 5-percent level.

Figure B-1. Silver maple decline on US 7 south of Shelburne, Vt., is apparent in views (a) and (b). Healthy trees are vigorously growing on the left side of the road while those on the lower, right side show declining growth and some dead limbs. In 1968, deicing salts drainage waters caused severe decline of the trees on the right (c). By 1969, the trees on the right had died. Those on the left side, which had not experienced highway drainage waters, remained vigorous.

growing on the west side of the highway (the left side of the photographs).

These pictures show the northern portion of the site to be at the bottom of a large slope. It is in this area that silver maple decline was most apparent. Trees located midway of this slope and on the east side of the highway have some damage while trees at the top of the slope are healthy on both sides of the road. Trees located at some distance from the bottom of the slope where the topography became level were also healthy on both sides of the highway.

All the silver maples shown on the west side of the highway were assigned a rating of 1 in 1967 and 1968, while a few in 1969 had a rating of 2. The silver maples shown on the east side of the road were generally given a rating of 4 with a few ratings of 3 in 1967; during 1968, most ratings were 5 with several at 4. In fact, the damage was so severe that during the late winter of 1968-69, many silver maples had to be removed by the Highway Department. Although silver maple damage was so severe that many trees died and had to be removed, there was no visible damage to the grassy vegetation in this area.

Higher concentrations of chloride and sodium were noted (Table B-1) in the leaf and twig tissue of the damaged silver maples as compared to healthy trees for all sampling periods except for sodium in the stems sampled on 4-5-69. For this sampling period, the sodium content in the stems increased drastically in both damaged and healthy trees, and no difference was noted for trees on either side of the highway. This effect did not occur for chloride. The concentration of phosphorus and magnesium in both tissue parts did not significantly differ for the trees on each side of the road. In several instances, significant differences were noted for the concentrations of potassium and calcium for the trees on the east and west sides of the highway. In these instances, the damaged silver maples contained higher concentrations of each of these elements in the leaf tissue and lower concentrations in the stem tissue except for potassium in the stem tissue sampled on 9-15-67, which was higher for the damaged trees. The concentrations of chloride, phosphorus, potassium, and magnesium were higher in leaf than in stem tissue except for chloride and phosphorus sampled on 9-13-67 for the east side of the highway. The concentrations of sodium and calcium were greater or the same for the stem tissue than for the leaf tissue in all but four cases. These exceptions include the calcium concentration for the trees sampled on 9-13-69 for both sides of the road and the sodium concentration of the trees located on the east side of the road for both the 9-13-68 and 6-24-69 sampling periods.

The concentration of chloride in the leaves and stems increased with higher tissue deterioration of silver maples (Fig. B-2). The increase was greater in the leaves than in the stems. No damage was observed when the concentration of chloride was less than 0.18 percent. Leaf scorch appeared when the chloride concentration of the leaves was above 0.20 percent and moderate scorching and defoliation occurred above 0.50 percent chloride. After death, a decrease in the concentration of chloride occurred in stem tissues that was at times even lower than that in healthy trees. Sodium (Fig. B-3) also gave similar results, but the relationship was less pronounced. The greatest increase in tissue sodium as related to increased symptom ratings occurred in the stem rather than the leaf tissue. The percentage range was also greater for the sodium tissue content although the actual range was an order of magnitude greater for the chloride tissue content.

DISCUSSION

Silver maple decline at the site resulted from increased concentrations of sodium and chloride in the leaves and twigs of the damaged trees. This deterioration did not affect the concentration of phosphorus or magnesium in the plant tissue, and the changes produced in the potassium and calcium content of the tissue could have resulted from a physiological imbalance produced in the tree by the high tissue content of sodium and chloride or from changes in the availability of potassium and calcium in the soil. The higher sodium content of the soil could displace exchangeable potassium and calcium thereby increasing its availability for uptake. In time, however, the availability of potassium and calcium could decrease due to leaching losses and increased plant uptake. It should also be pointed out that the total uptake of these elements was much lower for damaged than for healthy trees due to a decrease in total leaf and stem tissue in the deteriorated trees.

Examination of this site reveals that deicing salt sprays are of no consequence to the decline of these silver maples. No visible damage occurred to trees on the west side of the highway or to those on either side of the highway at the top or far bottom of the slope. Therefore, distance from the highway or prevailing winds could not be responsible for the observed phenomenon. Deterioration of the silver maples increased with higher exposure of the trees to roadside drainage. Dead trees were found at the bottom of the slope where drainage accumulation was a maximum, while no visual decline occurred at the top or far bottom of the slope where drainage accumulation was a minimum. However, some tree deterioration was noticed midway of the slope on the east side of the road where highway drainage occurred. Damage to the trees, therefore, appears to have resulted from the root uptake of sodium and chloride rather than to suspected salt spray (see Appendix A).

The grass turf appeared healthy even in the area where silver maple decline was severe. Apparently grassy vegetation is capable of tolerating high concentrations of deicing salts. Therefore, the suggestion by Holmes (*5*) that "the dying of grass should be sought where salt injury to trees is suspected" is not always applicable.

Because of drainage and the use of deicing salts, the soil on the east side of the highway was shown to contain a higher concentration of sodium and chloride than the soil on the west side of the road (see Appendix A). The largest salt concentration occurred in the late winter and then sharply decreased through the spring and summer. The maximum contribution of such salts to the osmotic pressure of the soil solution is less than 1.5 atm. and much lower during the period of most active water uptake by the trees. Therefore, the osmotic effect produced by the salt appears to be a minor factor to silver maple decline. This leads to the conclusion that the deterioration of the trees is probably caused by the toxicity of a specific ion rather than to an osmotic effect. Since the degree of injury observed is highly correlated with the concentration of chloride present in the leaves and stems, it seems reasonable to assume that chloride is the toxic ion. The concentration of sodium, in the leaves and especially the stems, is much higher in the damaged than in the healthy trees. It may also contribute to the over-all deterioration of the silver maples, although it does not appear to be totally responsible because high concentrations of sodium were sometimes recovered in trees exhibiting no salt damage.

The amount of salt present in trees varied through years and seasons depending on environment. However, the chloride content of the damaged trees was always three to four times greater in the leaves and two to four times higher in the stems than in respective portions of healthy trees. The differences between the damaged and healthy trees would have been wider if the dead trees on the east side of the road had been removed from the averages. Apparently, after death chloride, and in some cases sodium, is lost from the woody tissue. Therefore, tissue analysis of a dead or dying tree may fail to reveal large quantities of these ions.

The sodium content of the damaged trees was three to eight times higher in the leaves and two to six times higher in the stems than in healthy trees if the 4-5-69 sampling period is omitted. In this period, which is before leaf bud, the highest concentration of sodium in the stems was ob-

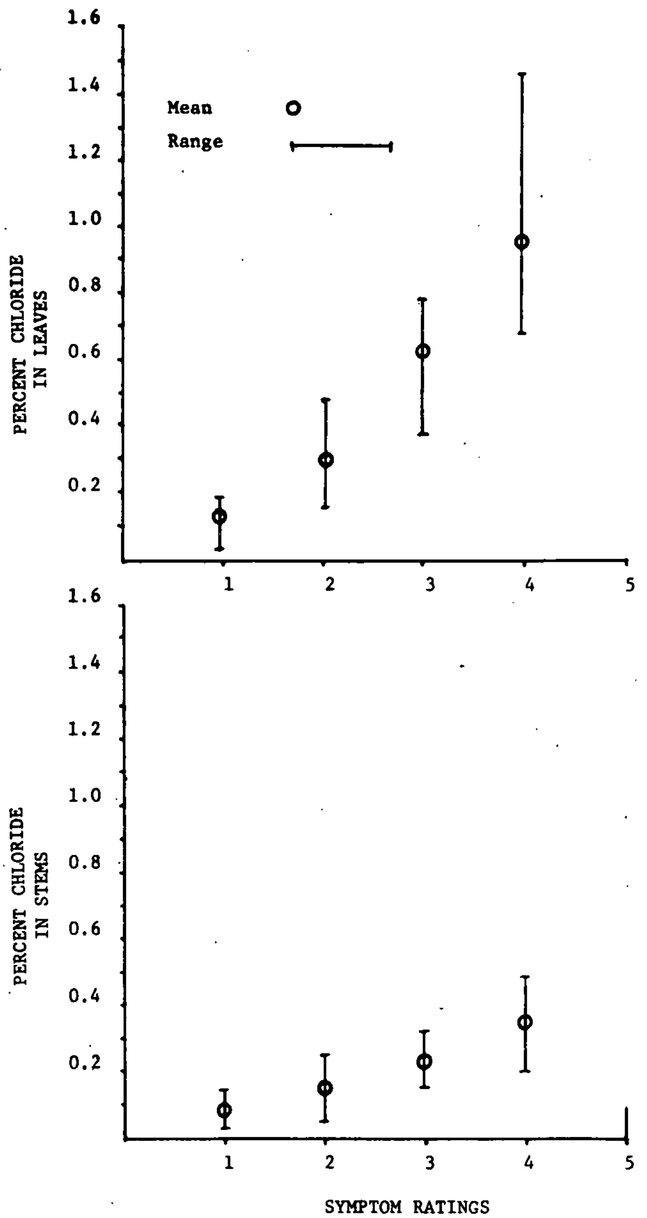

Figure B-2. Amount of chloride accumulated in the leaves and stems of silver maples as related to visual symptom ratings.

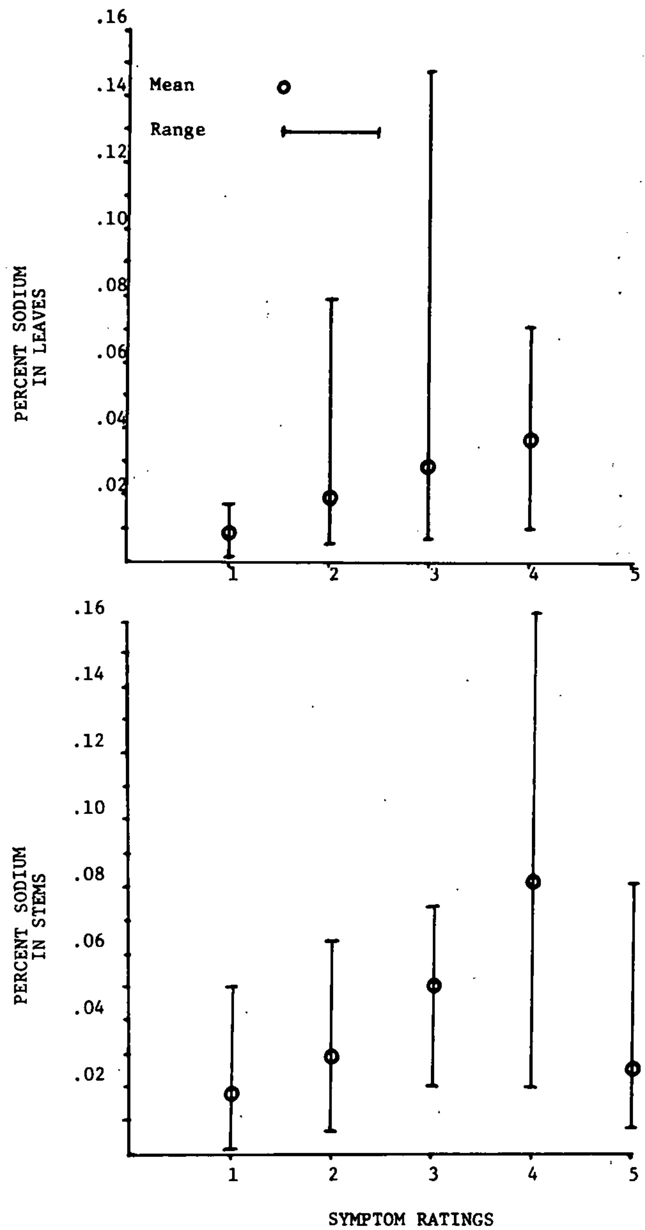

Figure B-3. Amount of sodium accumulated in the leaves and stems of silver maples as related to visual symptom ratings.

served for both the healthy and deteriorated silver maples, with values averaging above 0.14 percent. However, by the 6-24-69 period, when leaf growth and expansion had occurred, the sodium content of the healthy twigs dropped to 0.01 percent while those of the damaged trees averaged 0.06 percent. Possibly with leaf formation, the healthy trees were capable of transporting the stem sodium into the leaves thereby diluting the total amount of sodium present in the plant. This mechanism would not be operative in damaged trees due to severe defoliation. At this time, the healthy leaves averaged 0.01 percent sodium while the chlorotic leaves contained 0.08 percent sodium.

CONCLUSIONS

The study indicated that the use of highway deicing salts has produced an extensive silver maple decline on the east side of US 7. Salts produced an increase in the sodium and chloride contents of the soil solution manifested through increased uptake of these ions into the leaves and stems of the damaged trees. Deterioration of the silver maples resulted from chloride toxicity rather than the osmotic effect of the salts in soil solution. A chloride concentration of 0.20 percent produced leaf scorch; above 0.50 percent produced moderate leaf scorch, defoliation, and ultimate death of the tree. The concentration of sodium was much higher in the damaged than the healthy trees and may possibly have been one of the reasons for the over-all deterioration of the silver maples. However, it does not appear to be totally responsible because high concentrations of sodium were sometimes recovered in trees exhibiting no salt damage. It was noted that, with the onset of death, chloride and in some cases sodium was lost from the woody tissue. Therefore, tissue analysis of a dead or dying tree may fail to reveal large quantities of these ions. The effect of salt spray was apparently negligible.

The detrimental effects of deicing salts to roadside vegetation is evident; however, public safety demands their use. Therefore, woody vegetation should be located as far from the highway as practicable and pavement drainage should be directed away from tree roots. Where possible, the plant species should be chosen on the basis of salt tolerance (see Appendix C) and placed in a favorable medium.

APPENDIX C

TOLERANCE OF SEVERAL TREES AND SHRUBS TO SODIUM CHLORIDE AND CALCIUM CHLORIDE

The effects of salts on plants along roadsides have recently attained importance in the Northeastern and North Central United States. Studies (*1, 11, 13*) indicate that large applications of deicing salts have created a problem of maintaining sensitive plants where salts accumulate. Areas of plant injury from salts along roadways are sporadic, and damage is most common where natural vegetation or woody plantings are near the road edges. Salt damage is of concern because of the unsightliness and added costs of removing or replacing the plants.

High salt concentrations cause leaf burn, premature defoliation, and terminal growth die-back which may reduce the usefulness of the plants, destroy their aesthetic appearance, and can be lethal. Use of the most salt-tolerant native species is one approach for solving the problem of maintaining a vegetative cover along roadsides where deicing salts are a problem and where plantings are required. Some information is available on the salt tolerance of woody plants for the low rainfall areas (*7, 15, 16, 17*) and coastal areas (*18, 19*). However, little information is available on salt-tolerant trees and ornamental shrubs for use in the snow-belt states.

RESEARCH APPROACH

The purpose of this research was to determine the tolerance of several deciduous trees and shrubs and evergreen trees and shrubs to the commonly used deicing salts sodium chloride and calcium chloride (NaCl and $CaCl_2$). A rapid and practical approach was employed where salt tolerance was based on plant injury symptoms and survival under field conditions with various salt treatments.

Three separate field experiments with (a) deciduous trees, (b) deciduous shrubs, and (c) evergreen trees and shrubs were established in the spring of 1966 in three physiographic regions of Virginia: the mountains at Blacksburg, piedmont at Orange, and coastal plain at Warsaw. The soil series for the three locations were Groseclose, Nason, and Sassafrass, respectively. A split-plot design was used that allowed for 12 salt treatments assigned as the whole plots. Within each whole plot, six species were planted in random rows of nine plants on 3-ft centers. All treatments were replicated four times except for the deciduous shrubs at Blacksburg, which were replicated three times.

The salt treatment schedule, given in Table C-1, consisted of split application of varying levels of NaCl and $CaCl_2$

during the winter months. Both salts were applied in the solid form.

The species used were:

1. Deciduous trees—green ash (*Fraxinus pennsylvanica*), sugar maple (*Acer saccharum*), European white birch (*Betula pendula*), thornless honey locust (*Gleditsia triacanthos inermis*), tulip poplar (*Liriodendron tulipifera*), and redbud (*Cercis canadensis*).
2. Deciduous shrubs—tartarian honeysuckle (*Lonicera tartarica*), spring glory forsythia (*Forsythia intermedia spectabilis*), spirea (*Spiraea Vanhouttei*), amur privet (*Ligustrum amurense*), redflowered weigela (*Weigela Eva Rathke*), and rose (*Rosa multiflora*).
3. Evergreen shrubs and trees—creeping juniper (*Juniperus horizontalis plumosa*), Pfitzer juniper (*Juniperus chinensis Pfitzeriana*), Adam's needle (*Yucca filamentosa*), white pine (*Pinus strobus*), Norway spruce (*Picea abies*), and Canadian hemlock (*Tsuga canadensis*).

All plants used were bare-rooted in the seedling stage. Deciduous trees were single-stem and ranged between 12 and 18 in. high. All shrubs were pruned to a height of 12 to 14 in. before the seedlings were planted. Evergreen seedlings ranged between 6 and 12 in. high.

All species were rated according to their salt tolerance. Salt tolerance ratings were based on a numeral scale:

1. Healthy.
2. Slight leaf scorching.
3. Moderate leaf scorching, slight defoliation.
4. Severe leaf scorching, moderate defoliation, minor limb death.
5. Severe defoliation, extreme limb deterioration, or death.

TABLE C-1

SODIUM CHLORIDE AND CALCIUM CHLORIDE TREATMENTS APPLIED DURING THE WINTERS OF 1966–67, 1967–68, AND 1968–69

	TREATMENT (LB/ACRE)	DATE OF TREATMENT [a]		
Check:	0	—	—	—
NaCl:	1,500	1966–67	1967–68	1968–69
	3,000	1966–67	1967–68	1968–69
		—	1967–68	1968–69
	6,000	1966–67	—	—
		—	—	1968–69
	12,000	1966–67	—	—
	8,000	1966–67	—	—
$CaCl_2$:	1,500	1966–67	1967–68	1968–69
	6,000	1966–67	—	—
		—	—	1968–69
	3,000	—	1967–68	1968–69

[a] Split applications applied during late December through early March.

These plant symptoms were valid diagnoses because salt-treated plants were compared to untreated plants.

RESULTS AND DISCUSSION

Deciduous Trees

In June 1967, the deciduous trees at Blacksburg and Warsaw were rated according to their tolerance to NaCl and $CaCl_2$ (see Table C-2). The difference in response among species and the response of species to different salt treat-

TABLE C-2

AVERAGE SALT-TOLERANCE RATINGS FOR DECIDUOUS TREES (JUNE 1967) *

		NaCl (LB/ACRE)					$CaCl_2$ (LB/ACRE)		
SPECIES	CHECK	1,500	3,000	6,000	8,000	12,000	1,500	6,000	Mean †
Blacksburg									
Sugar maple	1.9	2.3	3.5	4.3	4.3	4.9	2.5	4.4	3.5c
White birch	2.0	1.9	2.0	4.4	2.9	4.8	1.8	4.0	3.0b
Honey locust	1.5	2.3	1.4	1.7	1.7	2.4	1.7	1.5	1.8a
Tulip poplar	3.8	4.0	4.6	5.0	4.5	5.0	4.4	4.8	4.5e
Redbud	3.0	3.0	4.3	4.9	5.0	4.9	1.9	4.3	3.9d
Mean †	2.5a	2.7a	3.2b	4.1cd	3.7c	4.4d	2.5a	3.8c	
Warsaw									
Green ash	2.0	1.6	3.3	4.9	4.8	4.9	2.9	4.4	3.6c
Sugar maple	1.8	1.5	2.2	3.0	4.1	4.6	2.0	4.1	2.9b
White birch	1.5	2.1	3.4	3.0	3.9	4.3	1.7	4.2	3.0b
Honey locust	1.5	1.4	1.6	1.6	1.6	1.8	1.5	1.6	1.6a
Tulip poplar	2.7	2.9	4.5	4.6	4.7	5.0	3.3	4.6	4.0d
Redbud	1.5	1.5	1.9	4.3	4.9	5.0	1.9	3.3	3.0b
Mean †	1.8a	1.8a	2.8b	3.6c	4.0c	4.2c	2.2ab	3.7c	

* Ratings are: 1 = healthy; 2 = slight leaf scorching; 3 = moderate leaf scorching, slight defoliation; 4 = severe leaf scorching, moderate defoliation, minor limb death; 5 = severe defoliation, extreme limb deterioration, or death.

† Mean values that have the same letters do not differ significantly.

ments were highly significant within both plant groups. Also, the species-salt treatment interactions were significant (ie., the relative differences in responses among plant species varied with a given salt treatment). These responses show that the species differ in their salt tolerance.

The average salt tolerance ratings of deciduous trees generally show that as the applied amount of salt increased, the injury symptoms became more distinct, as shown by the larger rating values. However, honey locust, a salt-tolerant plant, showed little injury even at the highest salt treatment. Comparisons among mean ratings for species across all salt treatments and salt treatments across all species are given in Table C-2. The mean ratings for the Blacksburg location showed plant tolerance to salts to increase in the order tulip poplar < redbud < sugar maple < white birch < honey locust. At Warsaw, plant tolerance increased in the order tulip poplar < green ash < redbud = white birch = sugar maple < honey locust.

Honey locust was very tolerant to both NaCl and $CaCl_2$. Plants surviving in June of 1967 were still healthy in August of 1969. White birch, sugar maple, and redbud were moderately tolerant to these salts, but there was serious injury to plots with high salt rates; and many of these plants failed to survive during the summer. Green ash and tulip poplar were injured by both NaCl and $CaCl_2$. Injury occurred even at the low salt-application rates; the higher salt rates killed most of the plants among these two species. Several of the green ash and tulip poplar trees died during July and August the first summer following salt treatment. Green ash was used in the experiment to replace a dogwood species that died. Due to late fall planting and poor survival, green ash is reported for the Warsaw area only. The late planting and small size of the trees when treated with salt may have contributed to the intolerance of green ash; however, Monk and Peterson (*7*) found the tree to be only slightly salt-tolerant.

Rating value 6 was added for the salt-tolerance ratings taken in August 1968 after the second winter treatments. This value was established to compensate for the plants that died during the first growing season following salt treatment. Therefore, only the plants living at the beginning of the second winter's salt treatments were assigned rating values from 1 to 5. Table C-3 gives the salt-tolerance rating for deciduous trees taken in August 1968. These values show relative salt tolerance similar to the first year's results, although ratings may be higher due to the addition

TABLE C-3

AVERAGE SALT-TOLERANCE RATINGS FOR DECIDUOUS TREES (AUGUST 1968) *

		SALT TREATMENT (LB/ACRE)									
		1967				1967 AND 1968			1968		
		NaCl			$CaCl_2$	NaCl		$CaCl_2$	NaCl	$CaCl_2$	
SPECIES	CHECK	6,000	8,000	12,000	6,000	1,500	3,000	1,500	3,000	3,000	MEAN †
					Blacksburg						
Sugar maple	2.5	4.4	5.2	5.5	5.0	2.0	4.3	2.4	4.0	2.4	3.8c
White birch	1.8	4.3	3.1	6.0	2.6	1.3	1.8	1.8	1.7	2.6	2.7b
Honey locust	1.8	1.9	2.2	2.9	1.8	1.8	2.2	2.0	2.1	1.9	2.1a
Tulip poplar	4.5	6.0	5.5	6.0	6.0	4.7	5.6	5.1	6.0	3.9	5.3d
Redbud	3.2	6.0	6.0	6.0	5.2	2.4	4.3	2.1	2.4	3.5	4.1c
Mean †	2.8ab	4.5e	4.4e	5.3f	4.1de	2.4a	3.6cd	2.7ab	3.2bc	2.9ab	
					Warsaw						
Green ash	2.4	5.6	5.8	5.7	5.8	1.8	3.1	1.8	1.8	2.6	3.6c
Sugar maple	1.2	3.1	3.6	5.3	4.2	1.5	3.3	1.9	1.9	1.7	2.6b
White birch	1.2	2.4	5.2	4.5	5.5	1.3	2.1	1.7	1.3	1.5	2.7b
Honey locust	1.9	2.8	2.1	2.6	3.1	1.7	1.6	1.8	2.0	2.1	2.2a
Tulip poplar	2.2	6.0	5.8	6.0	5.9	3.0	5.0	3.6	2.3	1.9	4.2d
Redbud	1.6	3.9	6.0	6.0	2.8	1.5	1.8	1.5	1.7	1.8	2.9b
Mean †	1.8a	4.0c	4.8d	5.0d	4.6cd	1.8a	2.8b	2.0a	1.8a	1.9a	
					Orange						
Green ash	2.2	6.0	6.0	6.0	3.8	1.2	4.4	2.8	1.5	1.9	3.6c
Sugar maple	1.3	2.7	3.2	5.1	3.0	1.8	2.2	1.9	2.0	2.0	2.5b
White birch	1.3	1.2	2.5	3.3	1.6	1.4	1.7	1.1	1.2	1.0	1.7a
Honey locust	1.6	1.7	2.6	1.9	1.5	1.8	1.5	1.7	1.4	1.8	1.8a
Tulip poplar	1.8	5.0	4.9	6.0	4.3	4.5	4.2	3.8	3.3	2.2	4.0c
Redbud	1.6	3.4	4.2	6.0	2.8	1.5	1.9	1.7	1.6	1.7	2.6b
Mean †	1.6a	3.3cd	3.9d	4.7e	2.8bc	2.0ab	2.6bc	2.2ab	1.8ab	1.8ab	

* Ratings are: 1 = healthy; 2 = slight leaf scorching; 3 = moderate leaf scorching, slight defoliation; 4 = severe leaf scorching, moderate defoliation, minor limb death; 5 = severe defoliation, extreme limb deterioration, or death.

† Mean values that have the same letters do not differ significantly.

of rating value 6. At Blacksburg, salt tolerance increased in the order tulip poplar < redbud = sugar maple < white birch < honey locust. For the Warsaw location, tolerance increased in the order tulip poplar < green ash < redbud = sugar maple = white birch < honey locust. At the Orange location, the order of salt tolerance was similar, tulip poplar = green ash < redbud = sugar maple < honey locust = white birch.

Salt tolerance of these plants at Warsaw in the third growing season is shown in Figure C-1. Plant injury was caused by 6,000 lb per acre of $CaCl_2$ applied the previous winter. Similar degrees of injury were found for the 6,000-lb NaCl treatment. Tulip poplar and sugar maple showed marginal leaf necrosis, while redbud, white birch, and honey locust showed no evidence of becoming chlorotic. Figure C-2 shows tolerance of honey locust.

At Blacksburg, redbud showed leaf injury with the 6,000-lb rates of $CaCl_2$ and NaCl. Leaf burn caused by these treatments was just as severe as for the sugar maple. The trees were of the same age because both areas were planted at the same time; however, because of the geographic location and soil, the redbud trees at Warsaw are from 12 to 18 ft tall while the plants at Blacksburg during the third growing season are 3 to 5 ft tall. Thus, it seems that redbud is damaged less by salts when it is of fairly large size or when it is growing rapidly. For example, Figure C-3 shows a comparison of the degree of salt injury on redbud and sugar maple for the Warsaw location. These plants were treated with 6,000 lb per acre of $CaCl_2$ the previous winter. This picture, taken the third growing season, shows marginal leaf burn on the sugar maple while redbud shows no injury symptoms. Figure C-4 shows severe leaf burn for tulip poplar having the same salt treatment as the sugar maple and redbud. Likewise, green ash in the third growing season did not show injury symptoms at salt rates where tulip poplar and sugar maple exhibited leaf burn.

Deciduous Shrubs

Salt-tolerance ratings made in 1967 for deciduous shrubs are given in Table C-4. Plant species, salt treatments, and species-salt treatment interactions were highly significant. Comparisons among mean ratings showed salt tolerance for the Blacksburg location to increase in the order rose = spirea < weigela < forsythia < honeysuckle = privet. At Warsaw, salt tolerance increased in order rose = spirea < weigela < forsythia = honeysuckle < privet. Data on salt tolerance taken in August 1968 showed similar plant ratings (Table C-5). Privet and honeysuckle survived all salt treatments and were most tolerant among the six species. Forsythia and weigela were intermediate, while spirea and rose were sensitive to both NaCl and $CaCl_2$. Monk and Wiebe (*17*) also found that spirea and rose were sensitive to NaCl and $CaCl_2$ salts and were much less tolerant than honeysuckle (*Lonicera japonica*).

The rating values show less salt injury for the Orange location as compared to the other two areas. The reason for this is attributed to the low fertility of the Nason soil, causing the plants on untreated plots to lack the vigor and appearance of healthy ones. These plant conditions made it difficult to comparably rate the shrubs. The relatively small differences in plant ratings with and without salt treatments may well be an expression of a salinity-fertility

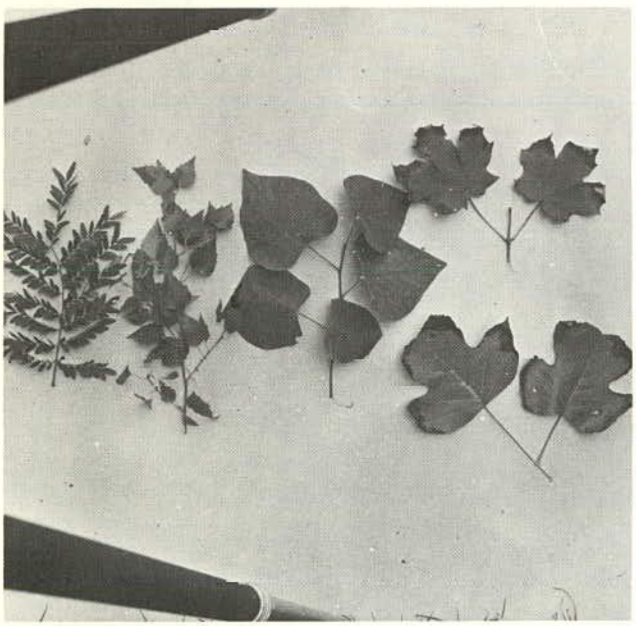

Figure C-1. Injury to various deciduous tree leaves during August caused by application of calcium chloride to the soil the previous winter. Leaves are, left to right, honey locust, green ash, redbud, sugar maple (top), and tulip poplar (bottom right).

Figure C-2. Deciduous trees show marked differences in tolerance to deicing salts. Note only honey locust, far left, survived the winter after an application of 12,000 lb of sodium chloride. Grass and other vegetation was also injured by soil applications of deicing salts.

Figure C-3. Compare the degree of salt injury to sugar maple with that to redbud, both of which were treated with 6,000 lb per acre of calcium chloride the previous winter.

Figure C-4. The tulip poplar shows severe leaf burn, having been treated with 6,000 lb per acre of calcium chloride the previous winter.

interaction. Statistical differences among the species existed only for three salt treatments (NaCl supplied at 6,000, 8,000, and 12,000 lb per acre in 1967).

The relative salt tolerance for five of the shrubs from the Warsaw location is shown in Figure C-5. Plants were treated with 6,000 lb per acre NaCl in winter of 1968-69 and the picture was made the following August. The plants are shown in order of increasing salt injury from left to right. Privet and honeysuckle showed little or no damage and had no visible leaf tip burns. Spirea was seriously injured showing complete leaf drop and dead woody tissue. The tolerance of these plants in August 1967 to 6,000 lb

TABLE C-4

AVERAGE SALT-TOLERANCE RATINGS FOR DECIDUOUS SHRUBS (JUNE 1967)*

SPECIES	CHECK	NaCl (LB/ACRE) 1,500	3,000	6,000	8,000	12,000	$CaCl_2$ (LB/ACRE) 1,500	6,000	MEAN †
				Blacksburg					
Honeysuckle	2.2	1.9	1.9	1.9	2.1	3.9	1.6	1.6	2.1a
Forsythia	1.7	2.0	2.2	3.0	4.0	4.9	1.6	3.3	2.8b
Spirea	2.0	3.3	4.6	4.9	4.9	5.0	3.0	5.0	4.0d
Amur privet	1.9	1.1	1.4	1.5	2.4	3.5	1.7	1.3	1.9a
Weigela	1.7	2.6	3.4	4.7	4.4	5.0	2.2	4.9	3.6c
Rose	2.8	3.7	3.9	4.7	4.7	5.0	3.6	4.4	4.1d
Mean †	2.1a	2.4ab	2.9bc	3.4cd	3.8d	4.5e	2.3ab	3.4cd	
				Warsaw					
Honeysuckle	2.0	1.8	2.0	2.9	3.8	4.0	1.4	2.2	2.4b
Forsythia	1.3	1.7	1.8	2.8	4.5	4.3	1.4	3.5	2.7b
Spirea	1.3	2.8	3.4	4.6	4.9	4.9	2.4	3.8	3.5d
Amur privet	1.1	1.0	1.1	1.9	4.4	4.2	1.1	2.3	2.1a
Weigela	1.2	1.9	2.2	4.0	4.8	4.5	1.5	3.7	3.0c
Rose	1.8	2.3	3.5	4.8	4.3	5.0	3.0	4.3	3.6d
Mean †	1.3a	1.9bc	2.3c	3.5d	4.4e	4.5e	1.8b	3.3d	

* Ratings are: 1 = healthy; 2 = slight leaf scorching; 3 = moderate leaf scorching, slight defoliation; 4 = severe leaf scorching, moderate defoliation, minor limb death; 5 = severe defoliation, extreme limb deterioration, or death.

† Mean values that have the same letters do not differ significantly.

per acre of $CaCl_2$ applied during the previous winter is given in Figure C-6. Only the privet and honeysuckle (left and right, respectively) were living. Weigela and forsythia shown in center of the picture and spirea and rose (not shown) were all dead. When the 6,000-lb-per-acre treatment was split so that half of the salt was applied in 1967-68 and the remaining half in 1968-69, less salt injury occurred. Many of the spirea plants even survived.

Salt injury is usually first observed on the tip of the leaves, commonly known as tip burn. As injury becomes more advanced, margins of leaves become chlorotic, leaves turn brown and drop prematurely. Terminal growth points of plants are severely injured by salts. Dead tissue impairs the aesthetic appearance and reduces the value of the plant for its intended purpose. Figure C-7 shows typical salt injury on forsythia and weigela. Increasing degrees of salt injury with increased amounts of deicing salts on spirea are shown in Figure C-8. For flowering shrubs, the number of flowers can be reduced by salt treatment. Figure C-9 shows severe reduction in flowering of forsythia concurrent with salt injury. The flower buds formed but failed to open.

Evergreen Shrubs and Trees

The average tolerance ratings after the first winter's salt treatments at the Blacksburg location indicate Pfitzer juniper to be most tolerant and hemlock least tolerant (Table C-6). Creeping juniper, white pine, and Norway spruce were intermediate and did not differ from each other statistically. At Warsaw, salt tolerance increased in the order hemlock ≦ Norway spruce < white pine ≦ Adam's needle < creeping juniper < Pfitzer juniper. August 1968 data (Table C-7) indicate increasing salt tolerance in the order hemlock < Norway spruce < white pine < Pfitzer juniper at Blacksburg. For the Warsaw area, plant tolerance increased in the order hemlock = Norway spruce < white pine < creeping juniper < Pfitzer juniper = Adam's needle. Because of poor survival, creeping juniper and Adam's needle were not reported for the Blacksburg location.

The six evergreen species can be divided into two groups: three salt-tolerant and three salt-sensitive plants. The salt-tolerant group included Pfitzer juniper, creeping juniper, and Adam's needle. White pine, Norway spruce, and hemlock were very sensitive to both NaCl and $CaCl_2$. During

TABLE C-5

AVERAGE SALT-TOLERANCE RATINGS FOR DECIDUOUS SHRUBS (AUGUST 1968) *

		SALT TREATMENT (LB/ACRE)									
		1967				1967 AND 1968			1968		
		NaCl			$CaCl_2$	NaCl		$CaCl_2$	NaCl	$CaCl_2$	
SPECIES	CHECK	6,000	8,000	12,000	6,000	1,500	3,000	1,500	3,000	3,000	MEAN †
					Blacksburg						
Honeysuckle	1.9	1.8	1.4	4.2	2.1	1.6	1.6	1.9	1.7	1.7	2.0a
Forsythia	1.6	4.7	5.2	5.7	3.9	2.9	2.7	2.3	2.2	1.9	3.3b
Spirea	1.9	5.7	5.3	5.7	5.4	2.8	5.3	3.7	2.7	2.1	4.1c
Amur privet	1.4	2.1	2.6	3.9	2.0	1.2	1.8	1.9	1.8	1.8	2.0a
Weigela	1.6	5.4	4.7	6.0	5.7	1.9	4.9	3.1	2.7	2.3	3.8bc
Rose	2.6	5.7	5.7	5.7	5.1	2.2	4.3	3.4	2.9	3.0	4.1c
Mean †	1.8a	4.2c	4.2c	5.2d	4.0c	2.1a	3.4bc	2.7ab	2.3a	2.1a	
					Warsaw						
Honeysuckle	1.3	2.7	3.6	6.0	3.0	1.3	1.1	1.2	1.7	1.7	2.4a
Forsythia	1.0	4.3	5.7	5.7	4.3	2.2	3.8	2.4	2.0	1.8	3.3b
Spirea	1.1	6.0	6.0	6.0	6.0	2.7	5.3	3.3	2.9	1.8	4.1c
Amur privet	1.1	1.4	4.6	3.6	2.4	1.2	1.7	1.8	1.1	2.0	2.1a
Weigela	1.3	4.4	6.0	5.8	6.0	2.2	3.0	1.3	1.1	1.6	3.3b
Rose	1.1	6.0	6.0	6.0	6.0	1.2	2.4	1.7	1.6	2.7	3.5bc
Mean †	1.2a	4.1c	5.3de	5.5e	4.6cd	1.8a	2.9b	2.0a	1.7a	1.9a	
					Orange						
Honeysuckle	1.8	1.7	1.6	1.2	1.9	1.7	1.4	1.7	1.8	1.5	1.6a
Forsythia	1.0	1.2	1.0	1.3	1.4	2.3	1.2	1.6	1.5	1.2	1.4a
Spirea	2.0	1.3	4.2	4.9	1.7	1.4	1.3	1.8	1.4	1.6	2.2b
Amur privet	1.3	1.4	1.2	1.2	1.8	1.2	1.3	1.2	1.7	1.3	1.4a
Weigela	1.2	1.4	1.5	1.6	2.0	1.5	2.1	1.8	2.2	1.8	1.7a
Rose	1.4	6.0	3.7	4.9	2.5	1.2	1.4	2.2	1.8	1.4	2.6c
Mean †	1.4a	2.2bc	2.2bc	2.5c	1.9ab	1.6a	1.4a	1.7ab	1.7ab	1.5a	

* Ratings are: 1 = healthy; 2 = slight leaf scorching; 3 = moderate leaf scorching, slight defoliation; 4 = severe leaf scorching, moderate defoliation, minor limb death; 5 = severe defoliation, extreme limb deterioration, or death.

† Mean values that have the same letters do not differ significantly.

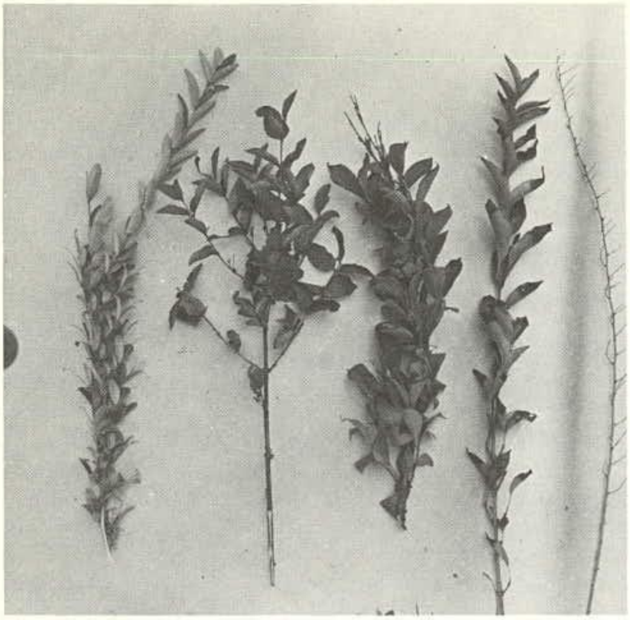

Figure C-5. Injury to various deciduous shrub leaves during August caused by application of sodium chloride to the soil the previous winter. Shrubs are, left to right, privet, honeysuckle, weigela, forsythia, and spirea.

Figure C-6. Deciduous shrubs vary in tolerance to deicing salts. After the previous winter's several split applications of calcium chloride, rose and spirea were dead by August, although honeysuckle and privet showed little injury and continued growing vigorously.

the first winter, even the lowest salt rates seriously injured and frequently killed these less tolerant species. Many of these plants were so injured by the first winter's salt treatments that they did not survive the following summer. Figure C-10, taken the latter part of the summer, shows that all three salt-sensitive species were killed by 3,000 lb

Figure C-7. Typical injury to deciduous shrub leaves and plant tissues caused by deicing salts is shown on forsythia (left two branches) and weigela (right two branches). The left branch for each shrub shows normal growth. Note for weigela that scorched leaves are the first of the symptoms after which small, and subsequently larger, woody tissues die.

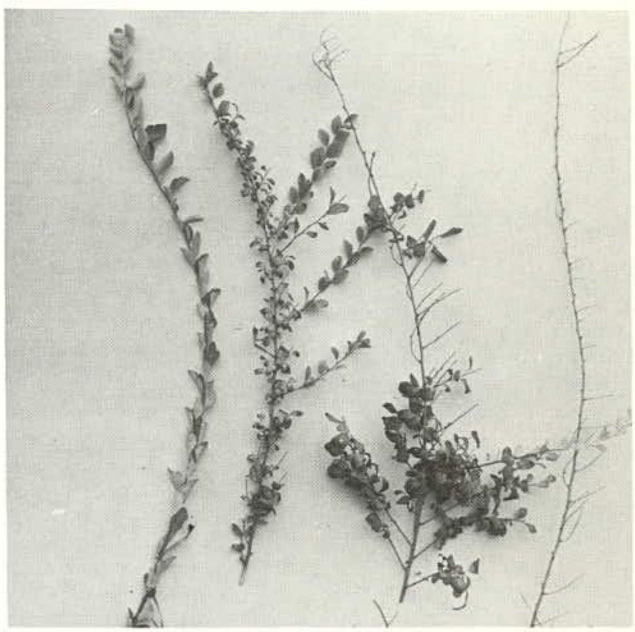

Figure C-8. The progressive injury to spirea foliage (left to right) is associated with increasing accumulations of chloride as a result of increasing increments of sodium chloride application. Mild chloride accumulation causes leaf burn; subsequently, as rates of application of deicing chloride salts increase, small twigs die, then larger branches.

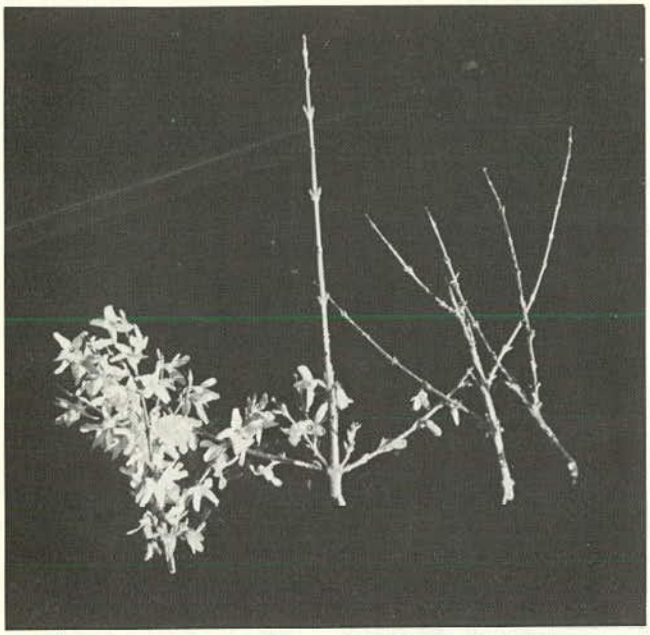

Figure C-9. Flowering of forsythia decreased and injury to leaves increased as more deicing salts were applied to the soil. Both calcium chloride and sodium chloride caused severe injury. Tissue damage was associated with chloride accumulation.

Figure C-10. Evergreen trees and shrubs vary in tolerance to deicing salts. Adam's needle, Pfitzer juniper, and creeping juniper showed little deicing salts injury even at high rates of application. White pine, Norway spruce, and hemlock were killed as a result of applications of deicing salts at medium-high rates.

per acre NaCl, while the salt-tolerant group remained healthy. Pfitzer juniper and Adam's needle, the most tolerant species, even survived the 12,000-lb NaCl treatment (Table C-7). The relative injury of five evergreen species in August 1969 caused by 6,000 lb per acre of NaCl applied during the previous winter is given in Figure C-11. Pfitzer juniper, creeping juniper, and Adam's needle showed no visible symptoms of salt injury. White pine developed slight needle burn, while hemlock was killed.

Comparisons across species of the mean injuries from

TABLE C-6

AVERAGE SALT-TOLERANCE RATINGS FOR EVERGREEN SHRUBS AND TREES (JUNE 1967)*

SPECIES	CHECK	NaCl 1,500	NaCl 3,000	NaCl 6,000	NaCl 8,000	NaCl 12,000	$CaCl_2$ (LB/ACRE) 1,500	$CaCl_2$ (LB/ACRE) 6,000	MEAN †
Blacksburg									
Creeping juniper	2.7	2.5	3.2	2.2	3.5	4.0	3.0	3.8	3.1b
Pfitzer juniper	1.5	2.0	2.4	1.9	2.3	3.5	2.6	2.0	2.3a
White pine	2.1	1.6	2.4	4.2	3.7	4.9	2.3	4.3	3.2b
Norway spruce	1.6	2.2	2.2	4.9	4.6	4.9	2.8	4.8	3.5b
Canadian hemlock	2.9	4.3	4.8	5.0	5.0	5.0	3.5	4.9	4.5c
Mean †	2.1a	2.5ab	3.0bc	3.6cd	3.8de	4.5e	2.9b	3.9de	
Warsaw									
Creeping juniper	1.3	1.4	1.6	3.5	4.0	4.7	1.6	2.4	2.6b
Pfitzer juniper	1.2	1.3	1.3	1.5	3.1	3.2	1.5	2.0	1.9a
Adam's needle	2.2	1.9	2.5	3.1	4.0	4.2	2.6	3.1	3.0c
White pine	1.8	2.0	2.9	4.0	4.7	4.6	2.4	3.8	3.3d
Norway spruce	1.5	2.0	3.1	4.3	4.8	5.0	2.6	4.5	3.6de
Canadian hemlock	1.8	3.0	3.0	4.7	5.0	5.0	2.3	4.3	3.7e
Mean †	1.7a	2.1ab	2.4b	3.5c	4.3d	4.4d	2.2ab	3.4c	

* Ratings are: 1 = healthy; 2 = slight leaf scorching; 3 = moderate leaf scorching, slight defoliation; 4 = severe leaf scorching, moderate defoliation, minor limb death; 5 = severe defoliation, extreme limb deterioration, or death.

† Mean values that have the same letters do not differ significantly.

TABLE C-7

AVERAGE SALT-TOLERANCE RATINGS FOR EVERGREEN SHRUBS AND TREES (AUGUST 1968)*

		SALT TREATMENT (LB/ACRE)									
		1967				1967 AND 1968			1968		
		NaCl			$CaCl_2$	NaCl		$CaCl_2$	NaCl	$CaCl_2$	
SPECIES	CHECK	6,000	8,000	12,000	6,000	1,500	3,000	1,500	3,000	3,000	MEAN †
					Blacksburg						
Pfitzer juniper	2.0	1.9	1.3	3.2	2.5	2.1	2.0	1.5	2.0	1.6	2.0a
White pine	1.4	4.2	3.3	6.0	4.5	1.9	2.1	2.1	2.5	2.8	3.1b
Norway spruce	1.6	6.0	5.5	6.0	6.0	2.0	3.8	3.5	3.3	2.8	4.0c
Canadian hemlock	3.5	6.0	5.8	6.0	6.0	5.1	6.0	5.7	5.2	3.1	5.2d
Mean †	2.1a	4.5e	4.0de	5.3f	4.8ef	2.8abc	3.5cd	3.2bc	3.2bcd	2.6ab	
					Warsaw						
Creeping juniper	1.3	4.0	4.9	4.5	3.4	2.6	2.7	1.7	1.8	1.6	2.8b
Pfitzer juniper	1.3	1.8	2.8	3.3	2.3	1.2	1.8	2.1	1.3	1.7	2.0a
Adam's needle	1.4	2.0	3.1	2.9	1.8	1.5	1.6	1.2	1.3	1.3	1.8a
White pine	1.4	6.0	6.0	6.0	4.9	1.9	4.2	2.7	1.5	2.3	3.7c
Norway spruce	2.0	6.0	6.0	6.0	6.0	6.0	4.1	6.0	1.7	3.0	4.7d
Canadian hemlock	1.2	6.0	6.0	6.0	5.3	6.0	5.8	5.2	4.2	3.1	4.9d
Mean †	1.4a	4.3d	4.8d	4.8d	4.0cd	3.2b	3.4bc	3.2b	2.0a	2.2a	

* Ratings are: 1 = healthy; 2 = slight leaf scorching; 3 = moderate leaf scorching, slight defoliation; 4 = severe leaf scorching, moderate defoliation, minor limb death; 5 = severe defoliation, extreme limb deterioration, or death.
† Mean values that have the same letters do not differ significantly.

NaCl and $CaCl_2$ for trees and shrubs (Tables C-2 through C-7) showed little or no difference for the rates of salts applied. However, when individual species were considered, the effect of these salts differed significantly. Field

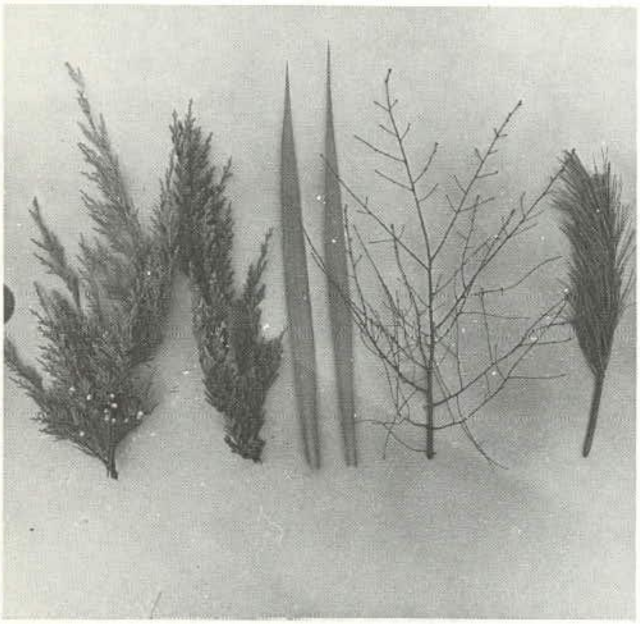

Figure C-11. Foliage of evergreens examined in August for injury as a result of the previous winter's split applications of 6,000 lb per acre of sodium chloride. Left to right is Pfitzer juniper, creeping juniper, Adam's needle, hemlock, and white pine.

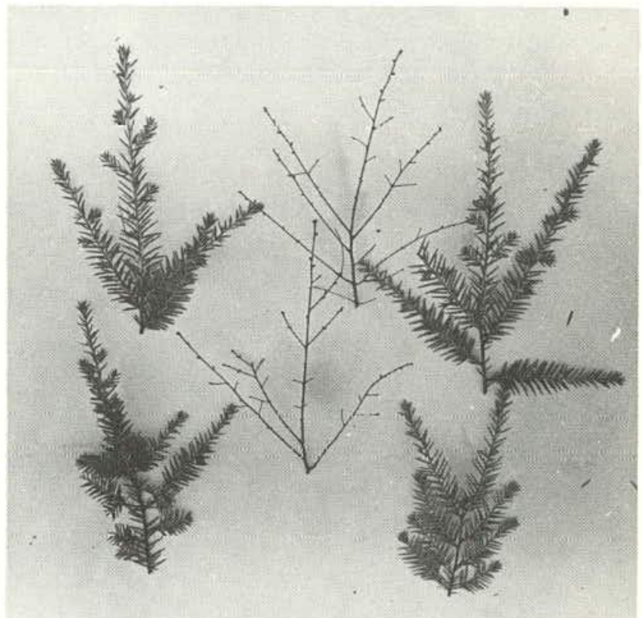

Figure C-12. Some plants, such as the Canadian hemlock, vary in tolerance to different kinds of deicing salts. Foliage of Canadian hemlock trees (left) that were grown without deicing salts applications (center) that died as a result of application of 6,000 lb per acre of sodium chloride the previous winter, and (right) that exhibit little injury after application of 6,000 lb per acre of calcium chloride. For small woody plants, it was found that sodium as well as chloride often accumulated in plant tissues.

observations in August 1969 showed slightly more injury to forsythia with $CaCl_2$ than for NaCl. When applying 6,000 lb per acre of the two salts for comparison in 1968-69, $CaCl_2$ caused more injury to white pine while NaCl gave more injury to hemlock. Figure C-12 compares the degree of injury of NaCl and $CaCl_2$ on hemlock. The two twigs on the left were untreated, the center twigs were treated with NaCl, and the two on the right were treated with $CaCl_2$. In most plots, hemlocks treated with NaCl were dead or dying, while the $CaCl_2$-treated plants showed little or no injury. White pine treated with $CaCl_2$ developed a reddish-brown needle tip burn, which gave the plants a bronze haze; for the sodium chloride treatment, such a burn on white pine was barely noticeable.

APPENDIX D

EFFECTS OF DEICING SALTS ON TISSUE COMPOSITION OF DECIDUOUS TREES

RESEARCH APPROACH

Field experiments described in Appendix C provided the basis for this part of the study.

Salt in the soil was extracted by shaking 25 g of soil in 50 ml of water and filtering. Plant tissue was dry-ashed, and sodium and calcium were determined with a flame spectrophotometer. Preliminary studies indicated that some chloride was lost during this dry-ashing process, even when calcium oxide was used (Table D-1). Thus, chloride measurements were made with separate extractions of plant tissue. Comparison of several solutions for analyses indicated very little difference between water and HNO_3-acetic acid solution and HNO_3 acid solutions for chloride determinations (Table D-1). Subsequently, chloride was removed from the plant tissue by equilibrating 1 g of tissue in 100 ml of 0.1 *N* HNO_3–10-percent acetic acid solution. Chloride was determined with an Aminco-Cotlove automatic chloride titrator. This titration procedure employed a 0.1 N HNO_3–10-percent acetic acid solution. This provided a rapid technique for measuring chloride in plant tissue.

RESULTS AND DISCUSSION

The amount of salt in the surface 10 in. of soil was directly related to the quantity of salt applied (Table D-2). Chloride and sodium concentrations (meq per 100 g of soil) measured in June 1967 increased consistently with the amount of salt applied the previous winter. The highest values for chloride and sodium were 7.69 and 6.66 meq per 100 g, respectively. In practical terms, a value of 1 meq of chloride per 100 g of soil is approximately 700 lb per acre. For sodium this would be about 460 lb per acre. These data show that very large quantities of salt remain in the plow layer during the growing season following

TABLE D-1

CHLORIDE CONTENT OF KENTUCKY 31 FESCUE AS RELATED TO THE SOLUTIONS AND PROCEDURES FOR EXTRACTING CHLORIDE FROM PLANT TISSUES

	CHLORIDE (% DRY TISSUE)			
TRIAL NO.	WATER	0.1N HNO_3	0.1N HNO_3, 10% ACETIC ACID	DRY ASH, CaO
1	1.01	1.01	1.03	0.94
2	1.01	1.00	1.01	0.98
3	1.02	1.02	1.02	0.88
4	1.02	1.01	1.02	0.90
5	0.96	0.99	1.02	0.82
6	1.02	1.00	1.01	0.86
7	1.01	1.01	1.02	0.94
8	1.02	0.99	1.02	0.94
9	1.02	1.00	1.02	0.89
10	1.02	0.99	1.02	0.91
Average	1.01	1.00	1.02	0.91

TABLE D-2

AVERAGE CHLORIDE AND SODIUM CONTENTS IN THE SURFACE 10 INCHES OF A SASSAFRAS FINE SAND LOAM (WARSAW, VA., JUNE 1967)[a]

	TREATMENT (LB/ACRE)	CHLORIDE (MEQ/100G SOIL)	SODIUM (MEQ/100G SOIL)
NaCl:	0	0.079	0.054
	1,500	1.049	0.810
	3,000	2.376	1.565
	6,000	3.706	2.740
	8,000	5.116	3.300
	12,000	7.692	6.660
$CaCl_2$:	1,500	1.287	0.041
	6,000	5.662	0.071

[a] Deicing salts had been applied the winter of 1966-67.

winter salt treatments. When considering only the 1,500 lb per acre NaCl treatment, 734 lb per acre of the 900 lb per acre of chloride applied was recovered. For sodium, 373 lb per acre of the 600 lb per acre applied (1,500 lb NaCl) remained in the soil.

These high salt concentrations in the soil were associated with the high salt content in the tree leaves (Table D-3). Missing values in the table are due to premature leaf drop induced by high rates of deicing salt. Values underlined represent only one of the three replications sampled. The chloride content of the leaves was considerably more than that for sodium; however, the amounts absorbed varied with the amount and level of salt applied and the plant species. All of the species absorbed more chloride than for the trees without salt; white birch and tulip poplar absorbed the most chloride, containing 0.566 and 0.640 percent, respectively. Frequently, the chloride contents of scorched leaves that remained in the severely injured trees which received the highest rates of salt were lower than values for those receiving intermediate rates of deicing salt. This may be attributed to leaching of salts from such severely injured leaves. The sodium content of the plant leaves was low except for white birch, which absorbed as much as 0.82 percent.

During the second winter, 1967-68, additional salt treatments were applied, and the salt concentrations in leaves and stems were measured in August 1968 (Table D-4). These values represent averages of two replications. Chloride content in the leaves was higher than the concentration in the stems. With the exception of white birch and tulip poplar, there were more chlorides in the leaves in the second year than for the first. Both leaves and stems contained chloride concentrations higher than normal, except for green ash.

The sodium content of both the leaves and stems for all species was low, and no plants contained abnormally high levels (Table D-5). Calcium content in the trees depended on whether NaCl or $CaCl_2$ was applied and also on plant species (Table D-6). However, the calcium contents of plants treated with $CaCl_2$ were only slightly higher than for the untreated plants. Plant injury cannot be attributed to these slight differences in calcium uptake.

The relationships between the salt concentration in the soil and the chloride and sodium content in leaves is shown in Figures D-1 and D-2. These data illustrate the plant species–salt treatment interactions (i.e., the amount of salt uptake by plants increases as the salt concentration in the soil increases, but this varies with the species).

A wide range of salt treatments from light to very heavy were applied the first year to determine where injuries occur. The very high salt rates were discontinued after the first winter because of severe plant injury and killing. However, the plants that survived with heavy rates of deicing salts, usually the most salt-tolerant species, were sampled the second growing season. At times, one or two plants of a salt-sensitive species in one replication survives with high salt rates. The reason for this variation is not apparent. Chloride concentrations in these plants were variable (Table D-7). Values underlined represent only one replication, as all trees in other replicates had died, but the data are presented to show the variation in such biological research. Missing data indicate that the plants had died as a result of deicing salts application. Sodium and calcium values appeared to be normal for these plants, indicating that chlorides are the harmful ions.

The relationship between the chloride and sodium content of the plants and the degree of salt injury depends on the plant species (Fig. D-3). Chloride concentration in the sugar maple increased concurrent with plant injury; but as plant injury became severe, chloride content was reduced. Similar trends with chloride injury were observed for white birch, tulip poplar, and redbud. Sodium content of sugar maple and white birch also increased with degree of injury, but to a lesser extent than for chloride. Tulip poplar and

TABLE D-3

PERCENTAGE OF CHLORIDE AND SODIUM CONTENTS IN LEAVES OF DECIDUOUS TREES (WARSAW, VA., JUNE 1967)[a]

		NaCl (LB/ACRE)					$CaCl_2$ (LB/ACRE)	
SPECIES	CHECK	1,500	3,000	6,000	8,000	12,000	1,500	6,000
			Chloride (% dry weight)					
Sugar maple	0.015	0.057	0.101	0.240	0.184	0.100[b]	0.088	0.118
White birch	0.010	0.389	0.566	0.415	0.213[b]	—[c]	0.137	0.367
Honey locust	0.016	0.028	0.064	0.151	0.078	0.162	0.024	0.057
Tulip poplar	0.007	0.295	0.614	0.467[b]	—[c]	—[c]	0.640	—[c]
Redbud	0.006	0.005	0.036	0.141	—[c]	—[c]	0.001	0.130
			Sodium (% dry weight)					
Sugar maple	0.012	0.026	0.056	0.120	0.124	—[c]	0.018	0.014
White birch	0.022	0.388	0.856	0.440	—[c]	0.820[b]	0.016	0.022
Honey locust	0.018	0.019	0.031	0.098	—[c]	0.054	0.016	0.013
Tulip poplar	0.030	0.015	0.040	0.013[b]	—[c]	—[c]	0.017	—[c]
Redbud	0.018	0.023	0.022	0.033	0.033[b]	0.039[b]	0.018	0.015

[a] The salts were applied during the winter of 1966-67.
[b] Live strees in only one replication.
[c] All trees in all replications died.

redbud had normal sodium concentrations with the deicing salt treatments. Both chloride and sodium concentrations of honey locust increased slightly with salt treatment, but this tree was not injured by deicing salts.

The chloride contents of leaves and stems during the second growing season, August 1968 (Fig. D-4), were variable but higher than normal values. The sugar maple gave a similar uptake pattern as the first year. Plant injury was associated with increased chloride uptake, but as injury became severe, chloride content in the leaves dropped. Apparently severely scorched or nearly dead leaves are not suitable samples because of loss of ions due to leaching.

TABLE D-4

CHLORIDE CONTENT OF LEAVES AND STEMS OF DECIDUOUS TREES (WARSAW, VA., AUGUST 1968)

		SALT TREATMENT (LB/ACRE)				
		1967 AND 1968			1968	
		NaCl		$CaCl_2$	NaCl	$CaCl_2$
SPECIES	CHECK	1,500	3,000	1,500	3,000	3,000
Leaves (% dry weight)						
Green ash	0.077	0.093	0.103	0.098	0.104	0.118
Sugar maple	0.041	0.162	0.306	0.164	0.208	0.173
White birch	0.078	0.143	0.166	0.089	0.201	0.113
Honey locust	0.121	0.128	0.469	0.214	0.159	0.201
Tulip poplar	0.079	0.130	0.149 [a]	0.132 [a]	0.206	0.516
Redbud	0.058	0.421	1.016	0.591	0.804	0.805
Stems (% dry weight)						
Green ash	0.032	0.024	0.117	0.022	0.023	0.026
Sugar maple	0.030	0.108	0.105	0.068	0.098	0.128
White birch	0.029	0.064	0.054	0.030	0.038	0.034
Honey locust	0.058	0.074	0.169	0.160	0.092	0.083
Tulip poplar	0.060	0.197	0.201 [a]	0.204	0.002	0.168
Redbud	0.036	0.128	0.144	0.098	0.094	0.112

[a] Live trees in only one replication.

TABLE D-5

SODIUM CONTENT OF LEAVES AND STEMS OF DECIDUOUS TREES (WARSAW, VA., AUGUST 1968)

		SALT TREATMENT (LB/ACRE)				
		1967 AND 1968			1968	
		NaCl		$CaCl_2$	NaCl	$CaCl_2$
SPECIES	CHECK	1,500	3,000	1,500	3,000	3,000
Leaves (% dry weight)						
Green ash	0.006	0.013 [a]	0.026 [a]	0.005 [a]	0.009 [a]	0.008 [a]
Sugar maple	0.004	0.004	0.018	0.062	0.025	0.006
White birch	0.007	0.007	0.009	0.004	0.015	0.008
Honey locust	0.009	0.008	0.010	0.006	0.004	0.006
Tulip poplar	0.007 [a]	0.006	0.006 [a]	0.004 [a]	0.005	0.005
Redbud	0.006	0.010	0.010	0.006	0.003	0.004
Stems (% dry weight)						
Green ash	0.006	0.011 [a]	0.034 [a]	0.004 [a]	0.004 [a]	0.003 [a]
Sugar maple	0.006	0.043	0.067 [a]	0.009	0.038	0.008
White birch	0.010	0.007	0.010	0.009	0.007	0.008
Honey locust	0.006	0.011	0.068	0.033	0.010	0.010
Tulip poplar	0.004 [a]	0.006	0.006 [a]	0.006	0.010	0.009
Redbud	0.002	0.004	0.004	0.004	0.006	0.006

[a] Live trees in only one replication.

TABLE D-6

CALCIUM CONTENT OF LEAVES AND STEMS OF DECIDUOUS TREES (WARSAW, VA., AUGUST 1968)

		SALT TREATMENT (LB/ACRE)				
		1967 AND 1968			1968	
		NaCl		$CaCl_2$	NaCl	$CaCl_2$
SPECIES	CHECK	1,500	3,000	1,500	3,000	3,000
Leaves (% dry weight)						
Green ash	0.31	0.26	0.39	0.50	0.34	0.61
Sugar maple	0.80	0.82	0.57	1.21	0.99	1.14
White birch	0.64	0.58	0.62	0.74	0.67	0.72
Honey locust	0.34	0.66	0.78	0.79	0.52	0.73
Tulip poplar	0.11	0.86	0.78 [a]	0.30	0.30	0.70
Redbud	1.26	1.38	0.92	0.84	1.21	0.86
Stems (% dry weight)						
Green ash	0.41	0.26	0.31	0.28	0.20	0.29
Sugar maple	0.51	0.55	0.62	0.65	0.37	0.45
White birch	0.14	0.26	0.15	0.16	0.18	0.13
Honey locust	0.12	0.30	0.18	0.25	0.46	0.36
Tulip poplar	0.22 [a]	0.18	0.14 [a]	0.18	0.10	0.18
Redbud	0.27	0.21	0.18	0.22	0.16	0.22

[b] Live trees in only one replication.

TABLE D-7

CHLORIDE CONTENT OF LEAVES AND STEMS OF DECIDIOUS TREES (WARSAW, VA., AUGUST 1968)

		SALTS APPLIED 1967 (LB/ACRE)			
		NaCl			$CaCl_2$
SPECIES	CHECK	6,000	8,000	12,000	6,000
Leaves (% dry weight)					
Green ash	0.077	0.166 [a]	— [b]	0.155 [a]	0.164
Sugar maple	0.041	0.314	0.269	— [b]	0.134
White birch	0.078	0.103	— [b]	0.070 [a]	0.069 [a]
Honey locust	0.121	0.370	0.170	0.180	0.254
Tulip poplar	0.079	— [b]	0.120 [a]	— [b]	— [b]
Redbud	0.058	0.641	— [b]	— [b]	0.601
Stems (% dry weight)					
Green ash	0.032	0.118 [a]	— [b]	0.022	0.077 [a]
Sugar maple	0.030	0.126	0.070	— [b]	0.072
White birch	0.029	0.015	0.023 [a]	0.027 [a]	0.037 [a]
Honey locust	0.058	0.070	0.084	0.134	0.122
Tulip poplar	0.060	— [b]	0.163	— [b]	— [b]
Redbud	0.036	— [b]	— [b]	— [b]	0.222

[a] Live trees in only one replication.
[b] All trees in all replications died.

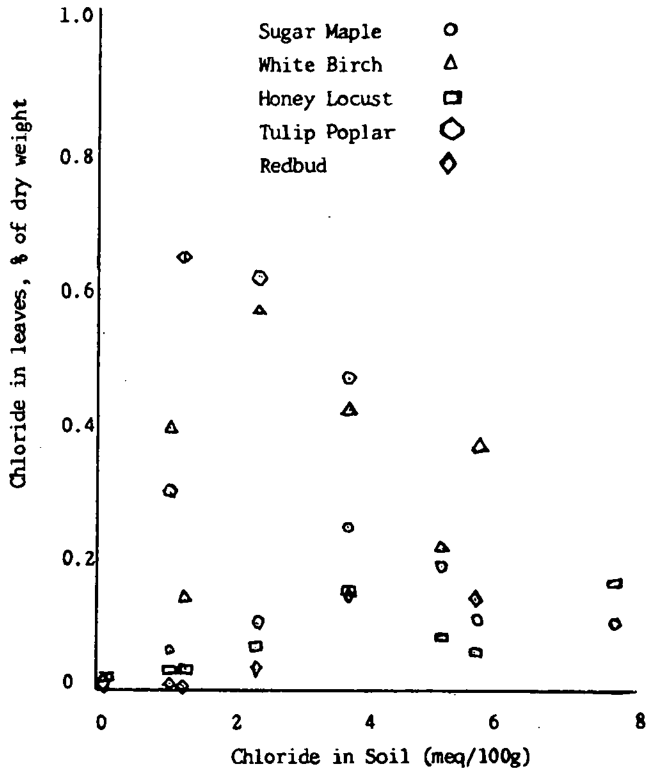

Figure D-1. Concentration of chloride in the soil related to the amount of chloride in deciduous tree leaves. Sodium chloride applied winter 1966–67; data collected June 1967.

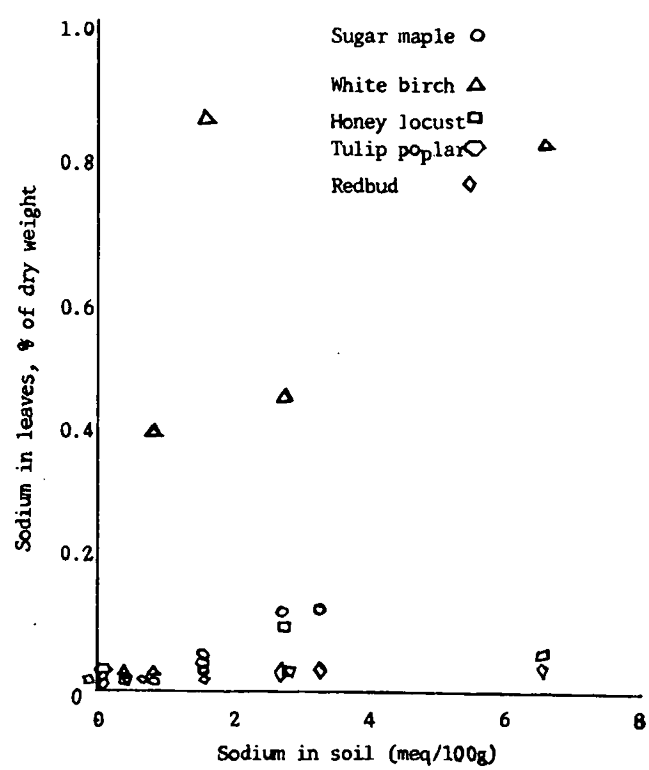

Figure D-2. Concentration of sodium in the soil related to the amount of sodium in deciduous trees leaves. Sodium chloride applied winter 1966–67; data collected June 1967.

TABLE D-8

CHLORIDE, SODIUM, AND CALCIUM CONTENT OF DECIDUOUS TREE LEAVES (WARSAW, VA., AUGUST 1969)

		SALT TREATMENT (LB/ACRE)			
		1968–69		1968	
SPECIES	CHECK	NaCl 3,000	$CaCl_2$ 3,000	NaCl 6,000	$CaCl_2$ 6,000
	Chloride (% dry weight)				
Green ash	0.049	0.060	0.096	0.091	0.129
Sugar maple	0.031	0.134	0.231	0.387	0.185
White birch	0.060	0.100	0.075	0.118	0.133
Honey locust	0.093	0.115	0.148	0.114	0.125
Tulip poplar	0.162	1.564	1.918	1.424	1.987
Redbud	0.061	0.190	0.178	0.207	0.196
	Sodium (% dry weight)				
Green ash	0.006	0.006	0.010	0.012	0.004
Sugar maple	0.004	0.056	0.007	0.013	0.010
White birch	0.008	0.004	0.009	0.004	0.008
Honey locust	0.011	0.011	0.005	0.004	0.005
Tulip poplar	0.005	0.019	0.012	0.017	0.011
Redbud	0.002	0.005	0.007	0.005	0.011
	Calcium (% dry weight)				
Green ash	0.44	0.34	0.47	0.31	0.48
Sugar maple	0.65	0.40	0.63	0.58	0.73
White birch	0.53	0.52	0.55	0.51	0.79
Honey locust	0.51	0.50	0.50	0.58	0.57
Tulip poplar	1.02	0.77	1.21	1.00	1.13
Redbud	0.60	0.64	0.89	0.76	0.95

The percentage of chloride in the leaves and stems of various trees is summarized for all tree species in Figures D-5, D-6, and D-7. Relatively high rates of chloride uptake occurred in both leaves and stems although higher in the former than the latter. The wide scatter of these data indicates the necessity for investigating different species. There were wide differences in salt absorption and injury among trees.

The sodium content of leaves during two years and of stems for one year of the trees was very low and not associated with injury (Fig. D-8). With the exception of white birch during the first year, very little sodium was taken up by the plants as indicated by leaf and stem composition. Salt damage to roadside trees has been partially attributed to sodium uptake (*1*). However, sodium does not appear to be the cause of salt injury to the species studied in these investigations. The calcium contents of various trees and leaves varied widely among tree species but calcium in these amounts could not be associated with injury among the various species (Fig. D-9).

The effect of NaCl and $CaCl_2$ on tree composition was determined the third growing season on selected salt treatments to compare the two deicing salts (Table D-8). Trees from three replications were analyzed and the average values show that the chloride content of the leaves was significantly increased by deicing salts, which fact supports the data collected the previous two years. The chloride concentration in the tulip poplar was extremely high. A comparison of the two salts shows that there were slightly higher

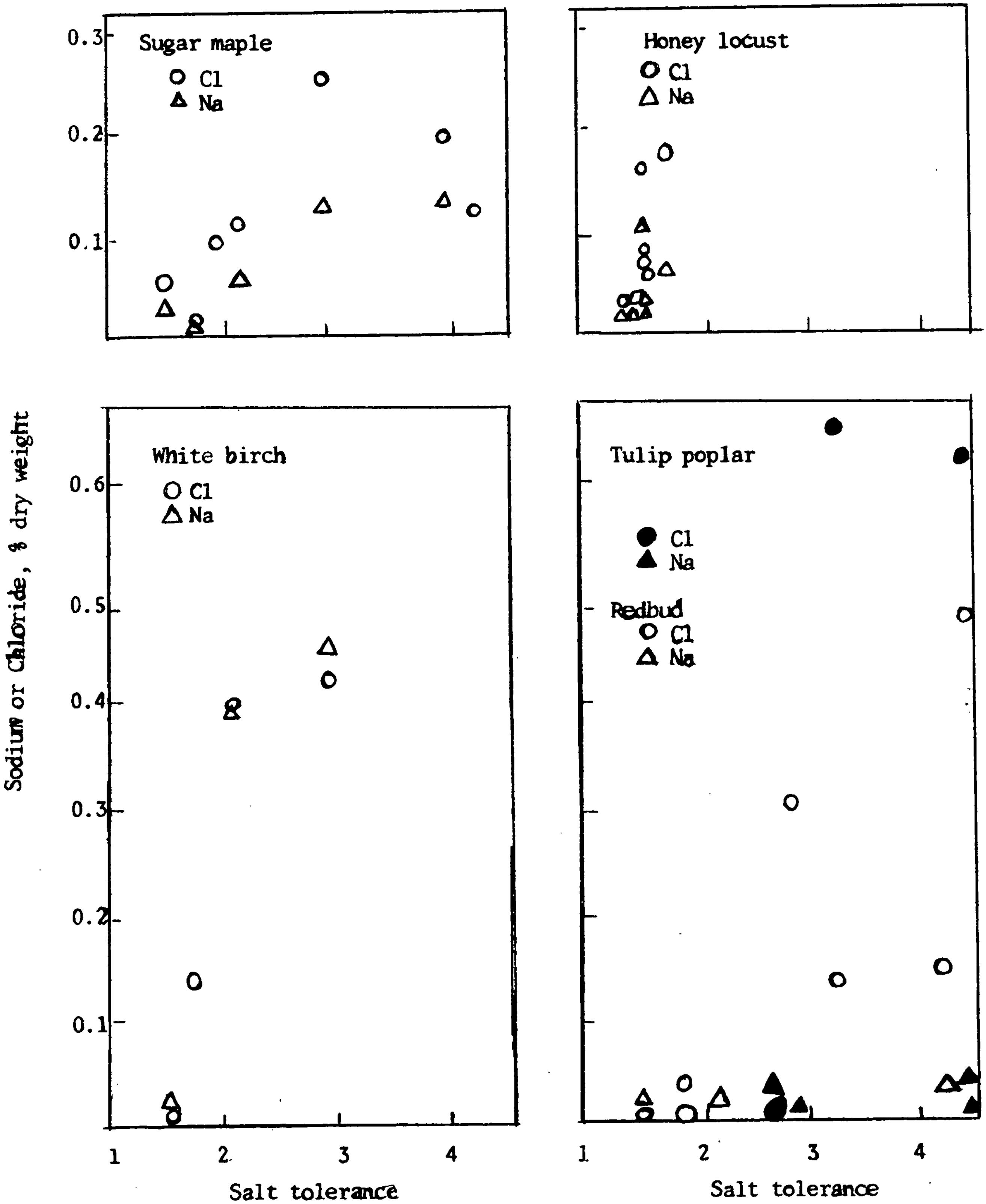

Figure D-3. Relationship between the tolerance to deicing salts of various deciduous trees and the chloride and sodium contents of their leaves. Data collected June 1967; 1=most tolerant.

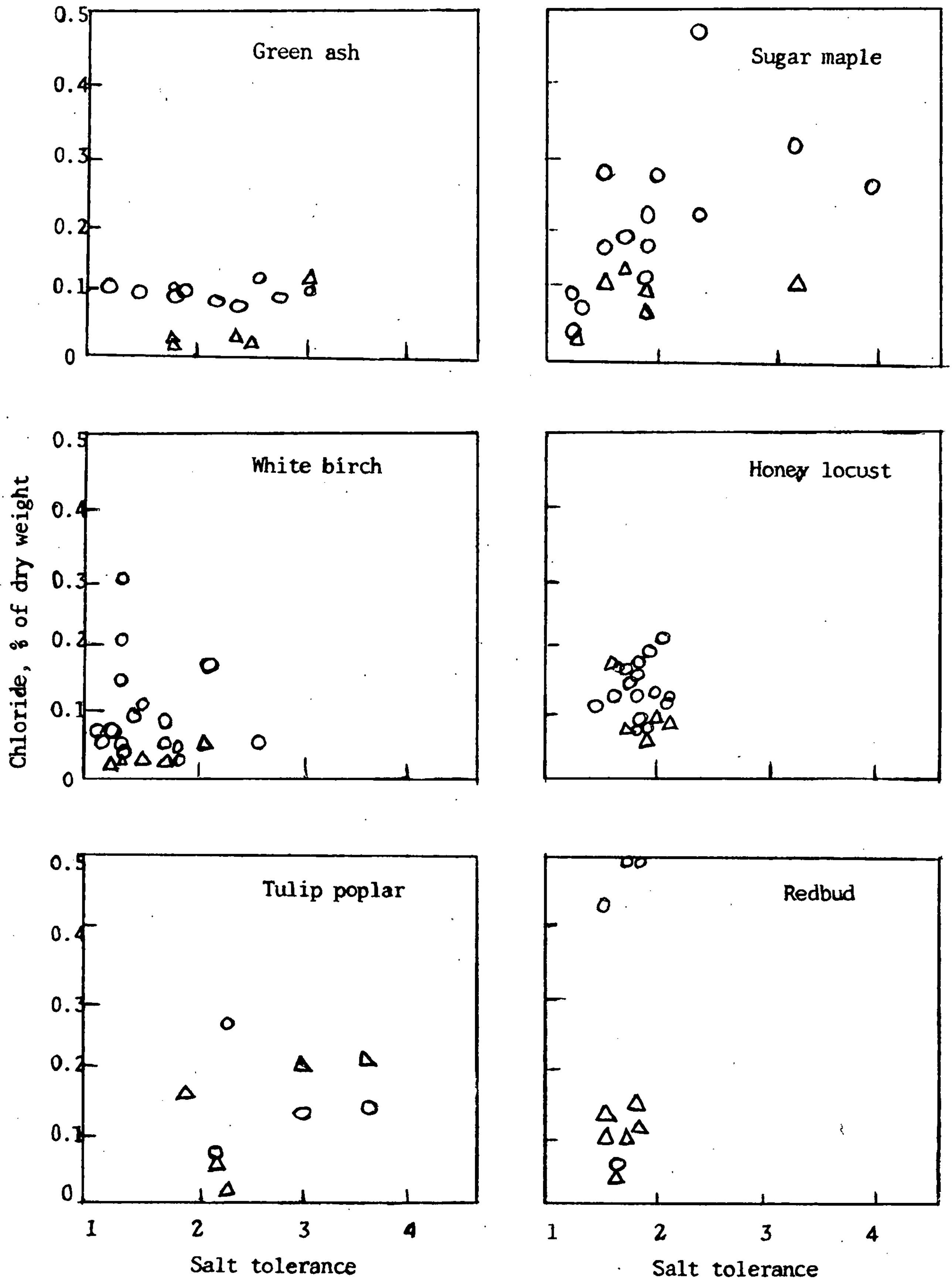

Figure D-4. Relationship between the chloride content of the leaves and stems of various deciduous trees and the degree of salt injury to the trees. Data collected August 1968; 1=most tolerant; ○=leaves; and △=stems.

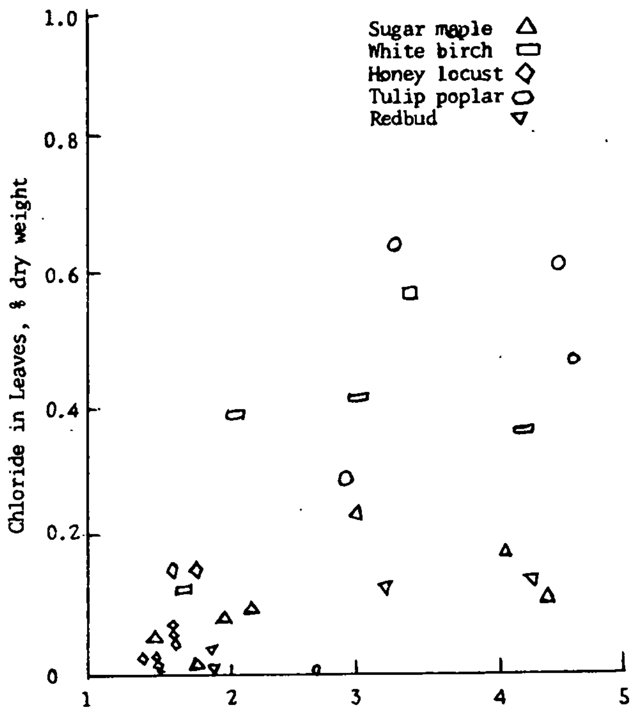

Figure D-5. Relationship between the chloride content of the leaves of various deciduous trees and the degree of salt injury to the trees. Data collected June 1967.

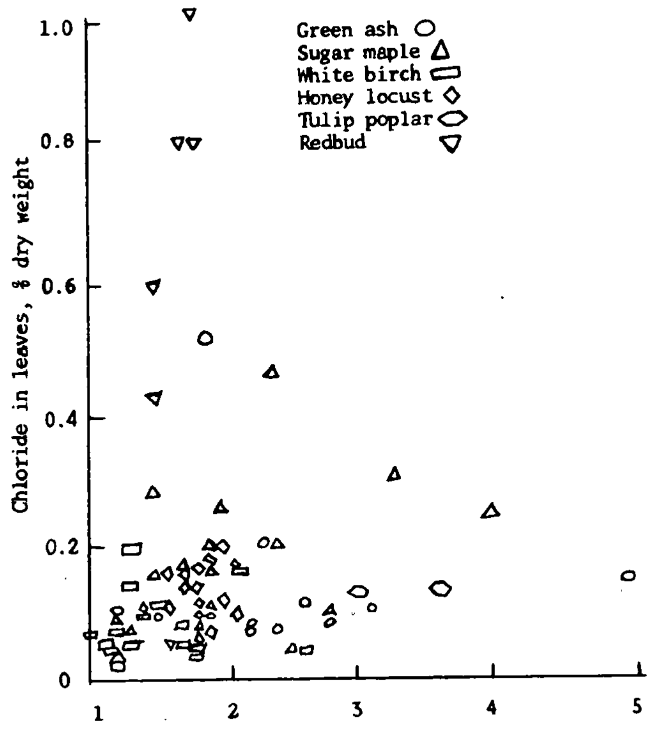

Figure D-6. Later relationship between the chloride content of the leaves of various deciduous trees and the degree of salt injury to the trees. Data collected August 1968.

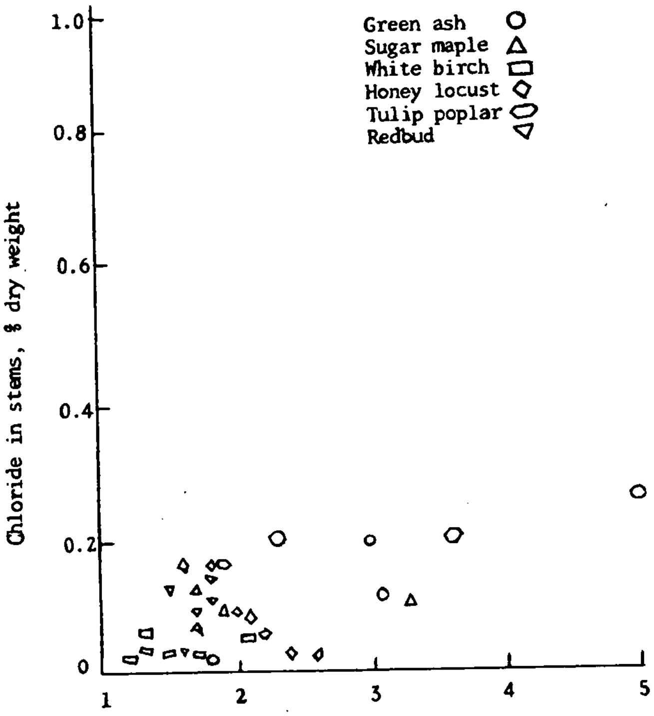

Figure D-7. Relationship between the chloride content of the stems of various deciduous trees and the degree of salt injury to the trees. Data collected August 1968.

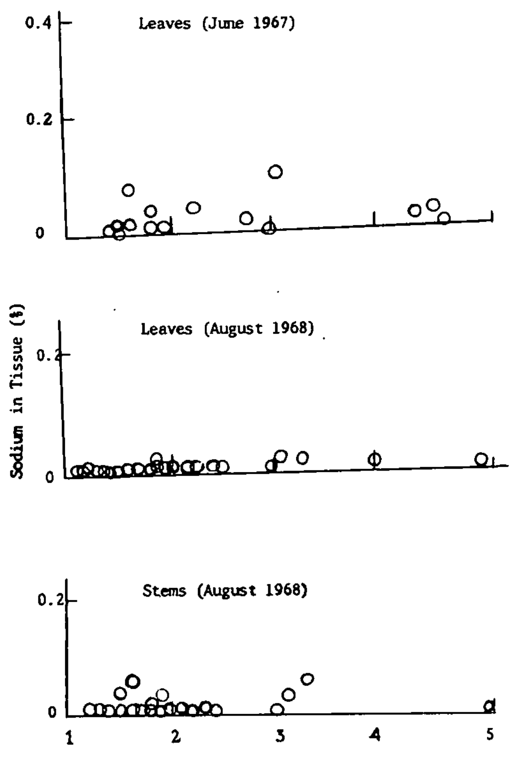

Figure D-8. Relationship between the sodium content (averaged) of leaves or stems of various deciduous trees and the degree of salt injury to the trees.

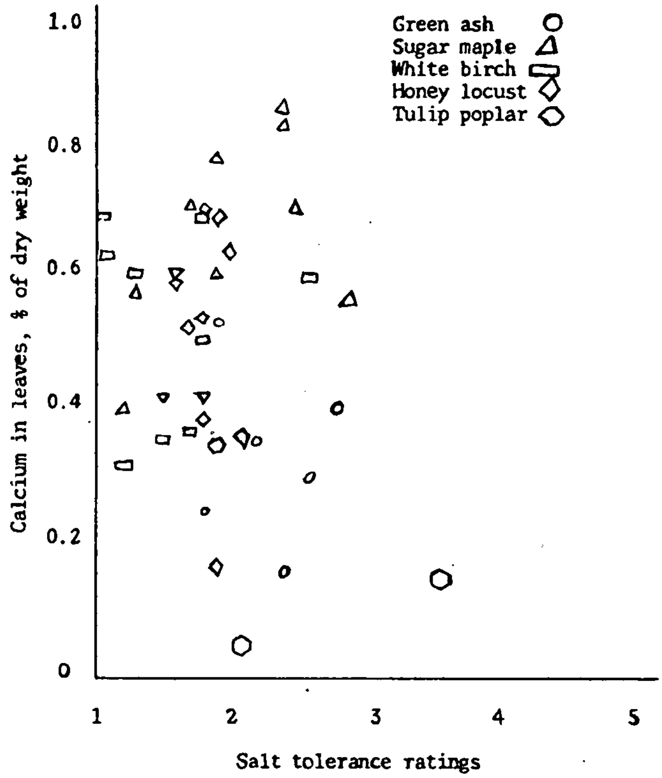

Figure D-9. Relationship between the calcium content of leaves of various deciduous trees and the degree of salt injury to the trees. Data collected August 1968.

chloride concentrations for the $CaCl_2$ than for NaCl. This response was expected because equal weights of the two salts were used, which means the amount of chloride applied was slightly more for the $CaCl_2$ treatments. This occurs because of the chemical makeup of the two salts. Sodium chloride treatments did not significantly affect the sodium content of the trees. However, the application of $CaCl_2$ caused slight increases in calcium uptake.

The relative degree of injury induced by the 6,000 lb per acre treatment is shown for sugar maple and tulip poplar in Figure D-10. The other tree species did not show leaf scorch. Values for salt uptake given in Table D-8 represent the composition of the deciduous tree leaves in photographs.

The seasonal changes in the chloride and sodium content of four of the trees studied was measured after 3,000 lb per acre NaCl was applied the previous winter (Figs. D-11 and D-12). Chloride content was low at the beginning of the growing season, but the uptake of salts after treatment occurred as early as April. In general, the chloride content of the stems and leaves was highest during the latter part of the summer but decreased during early winter. Sodium values were low and, with the exception of sugar maple, could have been considered normal. The sodium content of sugar maple was variable, but absorption was associated with the NaCl treatment.

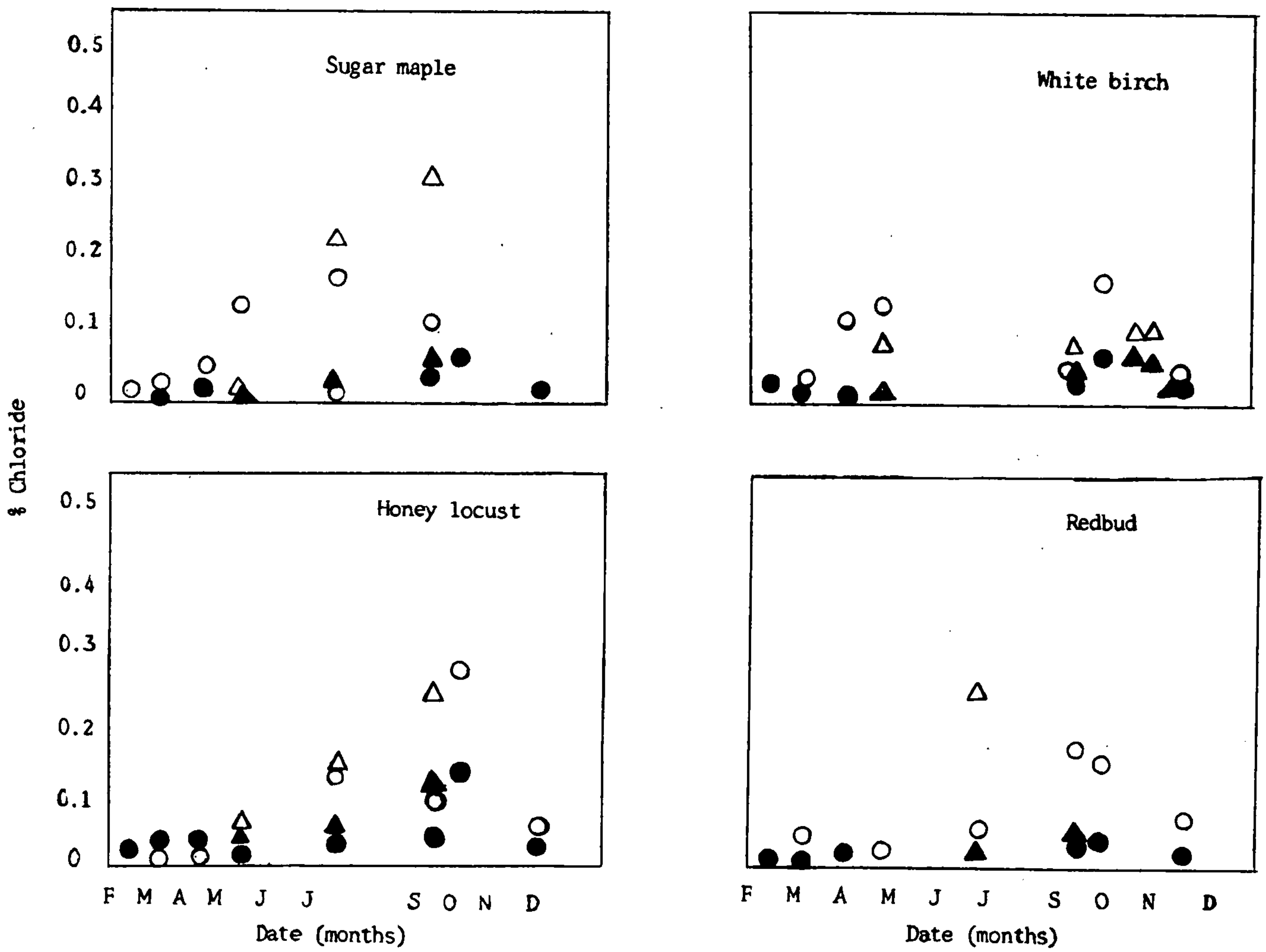

Figure D-11. Seasonal changes in the chloride content of various deciduous trees both treated with 3,000 lb per acre of sodium chloride and untreated (1968). Treated wood ○, leaves △. Untreated wood ●, leaves ▲.

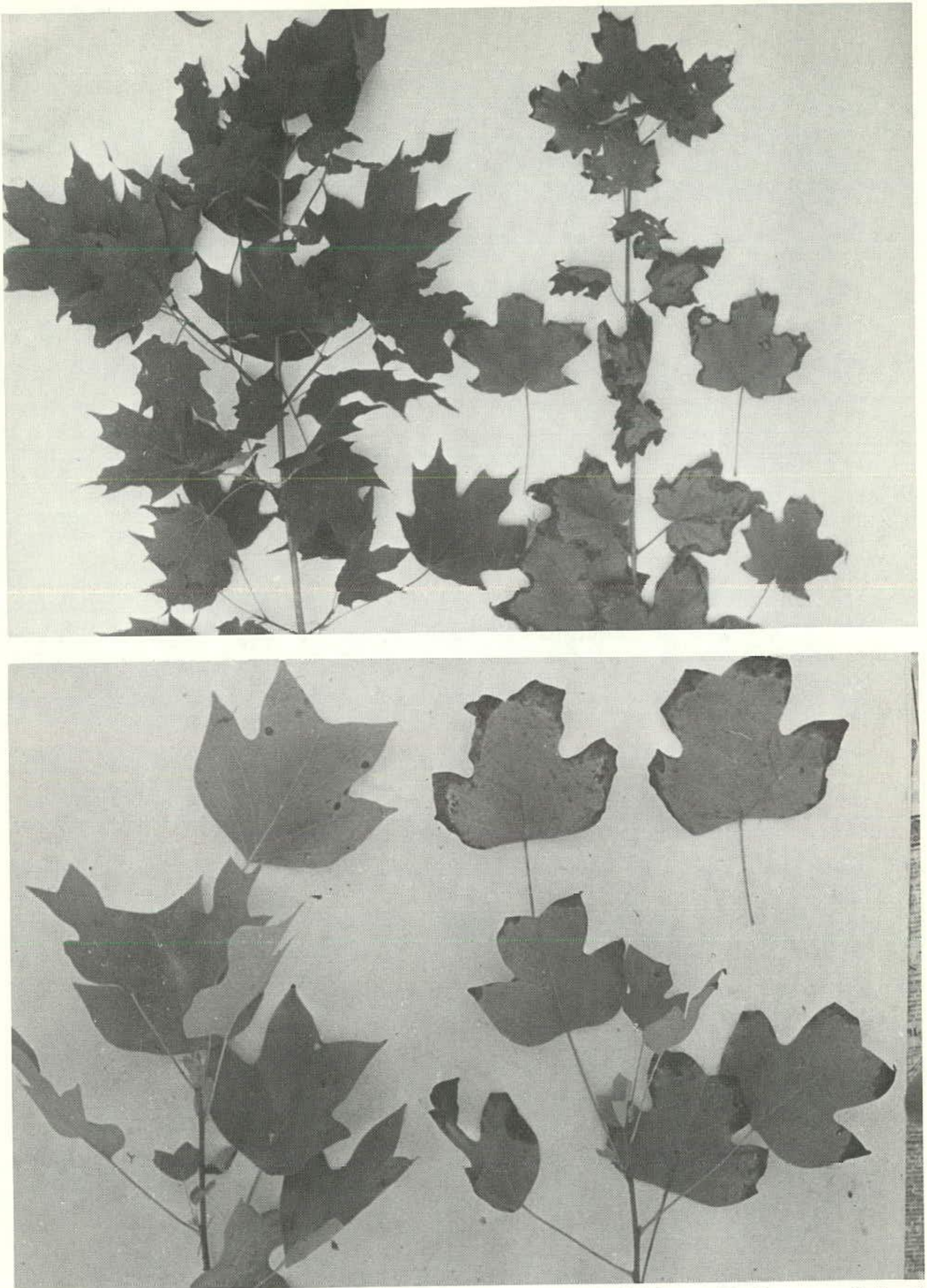

Figure D-10. Foliage of sugar maple (top) and tulip popular (below) showing salt injury resulting from an application of 6,000 lb per acre of sodium chloride applied winter 1968–69. Photographed August 1969.

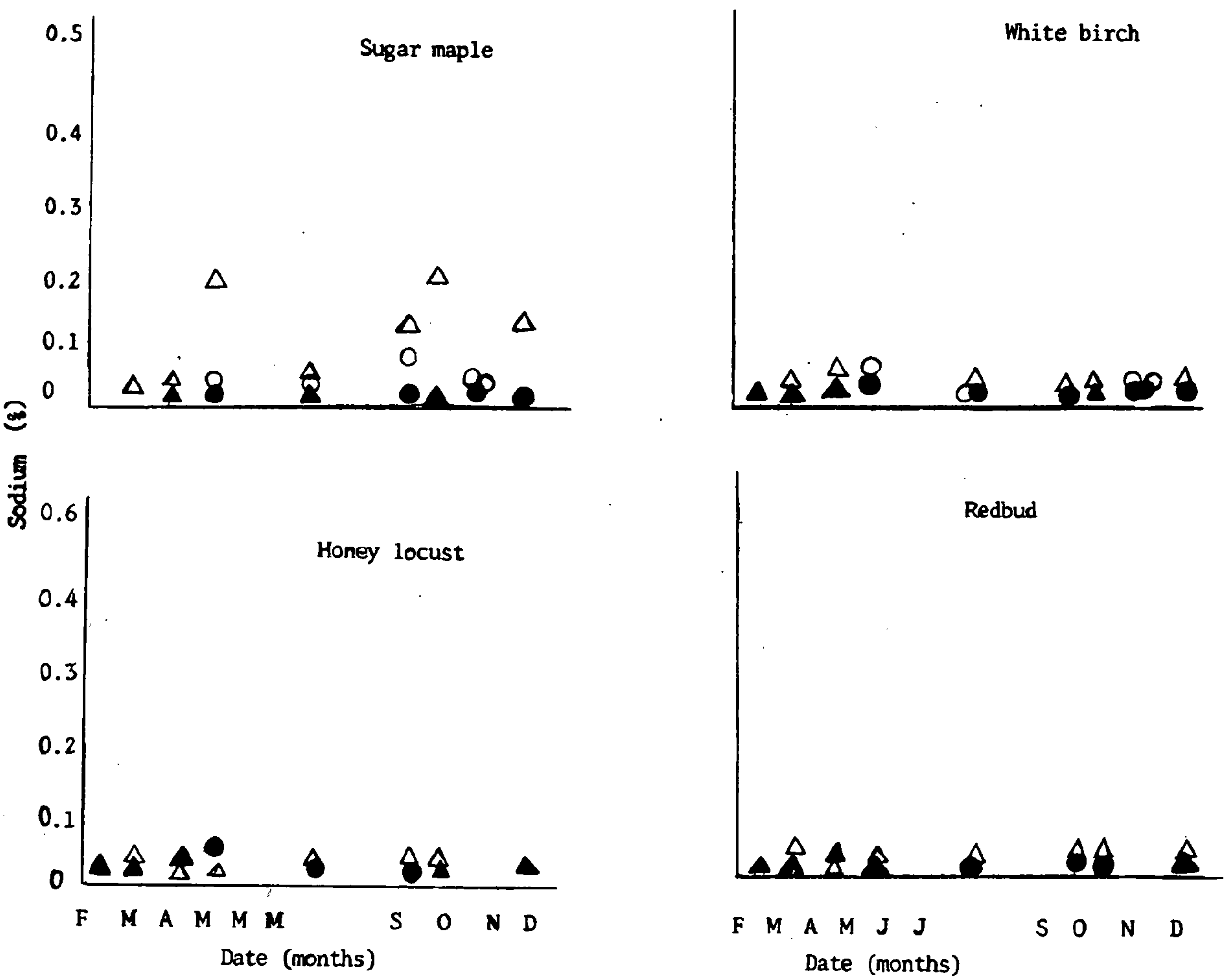

Figure D-12. Seasonal changes in the sodium content of various deciduous trees both treated with 3,000 lb per acre of sodium chloride and untreated (check) (1968). Treated stems △, leaves ○. Untreated stems ▲, leaves ●.

APPENDIX E

EFFECTS OF DEICING SALTS ON TISSUE COMPOSITION OF DECIDUOUS SHRUBS

Field experiments described in Appendix C provide the basis for this part of the study.

In June, after the first winter of salt treatments, chloride and sodium concentrations in the soil at Warsaw were high (Table E-1). It is significant that as much as 90 percent of the chloride, applied as calcium chloride, was recovered from the upper 10 in. of the soil; also 75 percent of the chloride that had been applied was recovered. The soil extracts had larger amounts of chloride as compared to sodium, which was attributed to the exchange of sodium for other cations on soil colloids. These values represent an average of four replications and agree closely with data previously reported for the Sassafras soil.

Chloride and sodium contents in leaves of deciduous shrubs were significantly increased by deicing salts, and the percents in tissue varied with plant species as well as the amounts and kinds of salt applied (Table E-2). Missing values are due to premature leaf drop induced by the salts making it impossible to get samples; also, the values underlined represent only one of the three replications as plant

TABLE E-1

CONCENTRATIONS OF CHLORIDE AND SODIUM IN AND PERCENTAGES RECOVERED FROM THE 1- TO 10-IN. HORIZON OF SASSAFRAS SOIL (WARSAW, VA., JUNE 1967) [a]

TREATMENT (LB/ACRE)		CHLORIDE (MEQ/ 100 G SOIL)	CHLORIDE % RECOVERY	SODIUM (MEQ/ 100 G SOIL)	SODIUM % RECOVERY
Check:	0	0.03	—	0.02	—
NaCl:	1,500	0.72	54	0.60	44
	3,000	1.47	56	1.15	44
	6,000	3.92	76	2.98	57
	8,000	5.26	76	3.83	55
	12,000	6.34	61	5.51	53
$CaCl_2$:	1,500	0.95	67	0.04	—
	6,000	5.06	92	0.07	—

[a] The data are averages of four replications.

tissue due to injury could not be obtained from the other replications. Both chloride and sodium contents of the leaves were much larger for shrubs having salt applications than for untreated shrubs. Significant differenecs occurred even for the lowest salt rates. Spirea and weigela contained 1.030 and 1.608 percent chloride, respectively, with only 1,500 lb per acre of NaCl. These two species were very sensitive to salt injury, and spirea did not survive with salts at rates above 3,000 lb per acre. The chloride content of all deciduous shrubs was much higher than for deciduous trees. Honeysuckle, forsythia, and weigela contained as much as 2 percent or more chloride. The sodium concentration was also relatively high, but the chloride concentration was much higher than that of sodium. Sodium values for the high rates of deicing salts were in the neighborhood of 1 percent of dry weight of tissue.

Definite relationships existed between the deicing salt concentration in the soil and salt uptake by plants. The percentage of chloride (Fig. E-1) and sodium (Fig. E-2) in leaves increased as the concentration of these ions in the soil increased. Near-maximum concentrations of chloride and sodium in the leaves occurred when chloride and sodium in the soil were approximately 4 meq per 100 g and 3 meq per 100 g, respectively. As the concentration of deicing salt in the soil continued to increase, the salt content of leaves tended to decline. It was observed that all species of shrubs studied followed this general uptake pattern. From these data, it appears that the high rates of salts may be causing very high osmotic pressure in soil solution, which could limit uptake due to pressure differences. Other explanations are possible physiological and morphological changes. For example, dead tissue in injured or highly susceptible plant species could cause leaching of salts due to dead tissue. Stunted growth (slow cell division and expansion) could cause increases in photosynthates, thereby reducing percentages of sodium and chloride because of the diluting influence.

During the second winter, certain salt treatments were continued and additional ones were added. These salt treatments caused significant increases on the chloride content of leaves, but data differed from the first winter. Spirea, weigela, and forsythia leaves were highest in chloride content, but the concentration was low as compared to the first year (Table E-3). Weigela and forsythia also contained high amounts of chloride in the stems. Honeysuckle, which had very high values for chloride absorption after

TABLE E-2

CONTENTS OF CHLORIDE AND SODIUM IN LEAVES OF DECIDUOUS SHRUBS (WARSAW, VA., JUNE 1967) [a]

SPECIES	CHECK	NaCl (LB/ACRE) 1,500	3,000	6,000	8,000	12,000	$CaCl_2$ (LB/ACRE) 1,500	6,000
		Chloride (% dry weight)						
Honeysuckle	0.007	0.480	1.005	2.329	1.08 [b]	0.739	0.090	0.946
Forsythia	0.154	0.389	0.842	2.242	1.434 [b]	1.020 [b]	0.869	2.011
Spirea	0.130	1.030	1.684	— [c]	— [c]	— [c]	1.074	— [c]
Privet	0.110	0.286	0.495	1.590	0.714	1.015	0.322	1.019
Weigela	0.069	1.608	1.706	2.050	1.736 [b]	1.980	1.208	1.646
		Sodium (% dry weight)						
Honeysuckle	0.009	0.295	0.553	0.889	0.754 [b]	0.945 [b]	0.014	0.018
Forsythia	0.017	0.398	0.678	0.878	— [c]	0.800 [b]	0.015	0.028
Spirea	0.010	0.180	0.530	— [c]	— [c]	— [c]	0.006	— [c]
Privet	0.008	0.228	0.666	1.079	0.486	0.687	0.009	0.015
Weigela	0.014	0.668	0.802	1.173	0.440 [b]	0.908	0.014	0.010

[a] The salts applied during 1966-67 winter are given in Table 2.
[b] Some plants in one of three replications survived.
[c] All trees in all replications died.

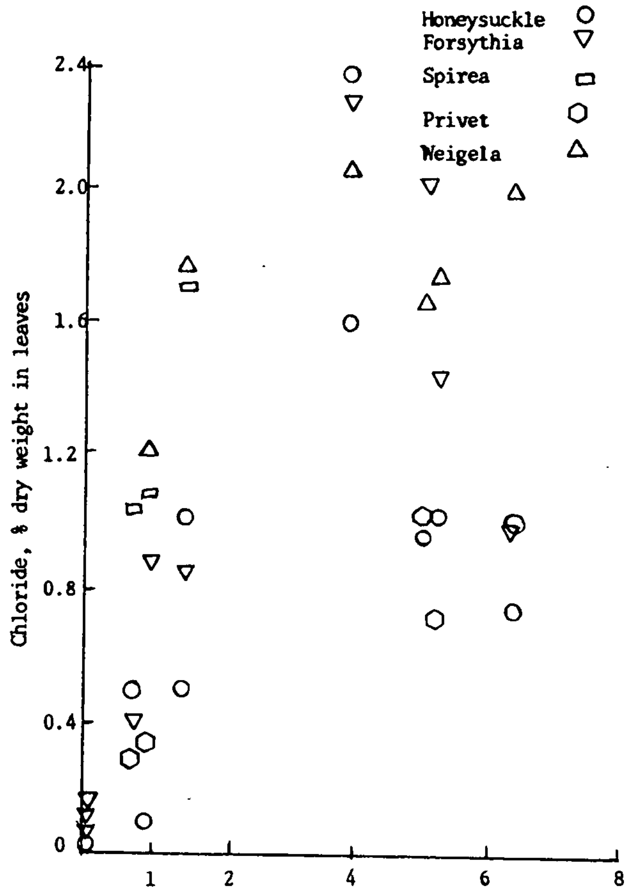

Figure E-1. Concentration of chloride in the soil related to the amount of chloride in deciduous shrub leaves (June 1967).

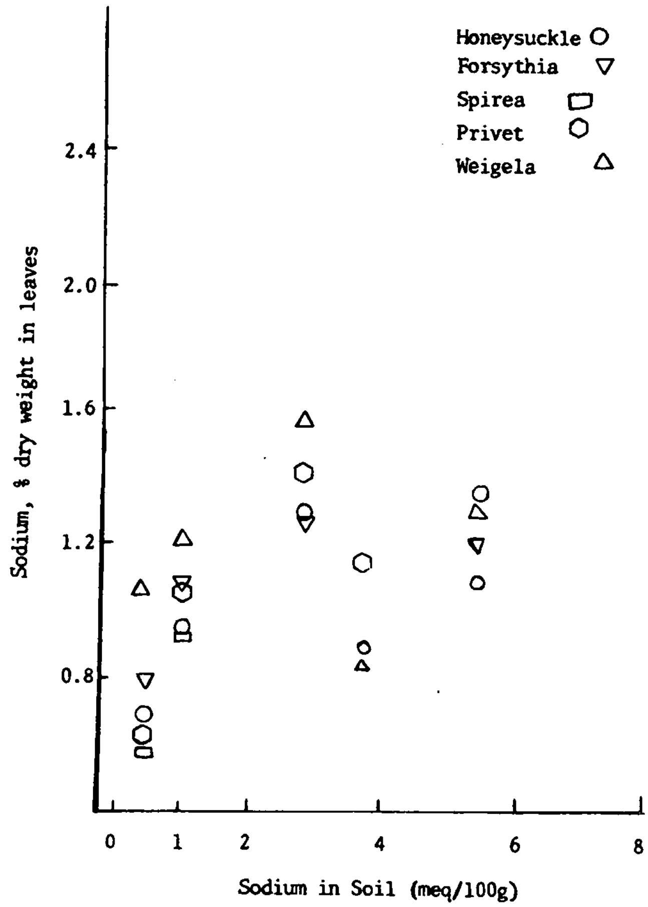

Figure E-2. Concentration of sodium in the soil related to the amount of sodium in deciduous shrub leaves (June 1967).

TABLE E-3

CHLORIDE CONTENT OF DECIDUOUS SHRUBS (WARSAW, VA., AUGUST 1968)

		SALT TREATMENT (LB/ACRE)				
		1967–68			1968	
		NaCl		$CaCl_2$	NaCl	$CaCl_2$
SPECIES	CHECK	1,500	3,000	1,500	3,000	3,000
Leaves (% dry weight)						
Honeysuckle	0.026	0.024	0.034	0.038	0.032	0.060
Forsythia	0.013	0.082	0.082	0.111	0.112	0.104
Spirea	0.193	0.640	—[a]	0.590	0.846	0.608
Privet	0.170	0.188	0.332	0.332	0.140	0.108
Weigela	0.142	0.485	0.668	0.659	0.498	0.684
Rose	0.108	0.343	0.151	0.324	0.454	0.385
Stems (% dry weight)						
Honeysuckle	0.026	0.008	0.018	0.009	0.022	0.021
Forsythia	0.041	0.132	0.134	0.118	0.122	0.121
Spirea	0.019	0.082	—[a]	0.042	0.061	0.064
Privet	0.035	0.038	0.044	0.042	0.036	0.066
Weigela	0.094	0.202	0.398	0.458	0.484	0.448
Rose	0.032	0.068	0.041	0.038	0.164	0.111

[a] All plants died.

the first winter's treatments, contained low levels during the second winter. The chlorides in leaves were much higher than in stems, except for forsythia where the values were similar (Table E-3).

The sodium contents of the leaves and stems of the shrubs were very low and not significantly affected by salt treatments the second winter (Table E-4).

The calcium content of the leaves was consistently higher with $CaCl_2$ treatment than with NaCl (Table E-5).

The percentage of calcium in leaves was higher than in stems, but the calcium content of rose was much higher than for other species.

The relationship between the percentages of chloride and sodium in the leaves and the degree of salt injury is shown in Figure E-3. Relationships are also given for the per-

TABLE E-4

SODIUM CONTENT OF DECIDUOUS SHRUBS (WARSAW, VA., AUGUST 1968)

		SALT TREATMENT (LB/ACRE)				
		1967–68			1968	
		NaCl		$CaCl_2$	NaCl	$CaCl_2$
SPECIES	CHECK	1,500	3,000	1,500	3,000	3,000
		Leaves (% dry weight)				
Honeysuckle	0.001	0.001	0.002	0.006	0.004	0.004
Forsythia	0.001	0.004	0.002	0.001	0.007	0.001
Spirea	0.002	0.001	—[a]	0.001	0.001	0.001
Privet	0.001	0.012	0.029	0.005	0.015	0.004
Weigela	0.008	0.013	0.013	0.011	0.008	0.011
Rose	0.003	0.009	0.004	0.003	0.004	0.002
		Stems (% dry weight)				
Honeysuckle	0.003	0.006	0.003	0.004	0.001	0.003
Forsythia	0.002	0.006	0.015	0.007	0.028	0.003
Spirea	0.001	0.003	—[a]	0.004	0.003	0.004
Privet	0.004	0.034	0.036	0.007	0.033	0.006
Weigela	0.012	0.024	0.013	0.007	0.009	0.005
Rose	0.003	0.003	0.002	0.001	0.003	0.001

[a] All plants died.

TABLE E-5

CALCIUM CONTENT OF DECIDUOUS SHRUBS (WARSAW, VA., AUGUST, 1968)

		SALT TREATMENT (LB/ACRE)				
		1967–68			1968	
		NaCl		$CaCl_2$	NaCl	$CaCl_2$
SPECIES	CHECK	1,500	3,000	1,500	3,000	3,000
		Leaves (% dry weight)				
Honeysuckle	0.76	0.64	0.98	0.96	0.48	0.57
Forsythia	0.33	0.45	0.42	0.64	0.41	0.66
Spirea	0.35	0.28	—[a]	0.50	0.35	0.42
Privet	0.56	0.29	0.28	0.49	0.30	0.44
Weigela	0.43	0.40	0.38	0.38	0.31	0.41
Rose	0.31	0.76	0.55	0.98	0.58	0.93
		Stems (% dry weight)				
Honeysuckle	0.09	0.07	0.06	0.09	0.39	0.08
Forsythia	0.05	0.01	0.04	0.08	0.07	0.12
Spirea	0.15	0.14	—[a]	0.26	0.19	0.25
Privet	0.06	0.02	0.02	0.07	0.03	0.04
Weigela	0.07	0.07	0.08	0.02	0.07	0.08
Rose	0.40	0.48	0.24	0.33	0.34	0.45

[a] All plants died

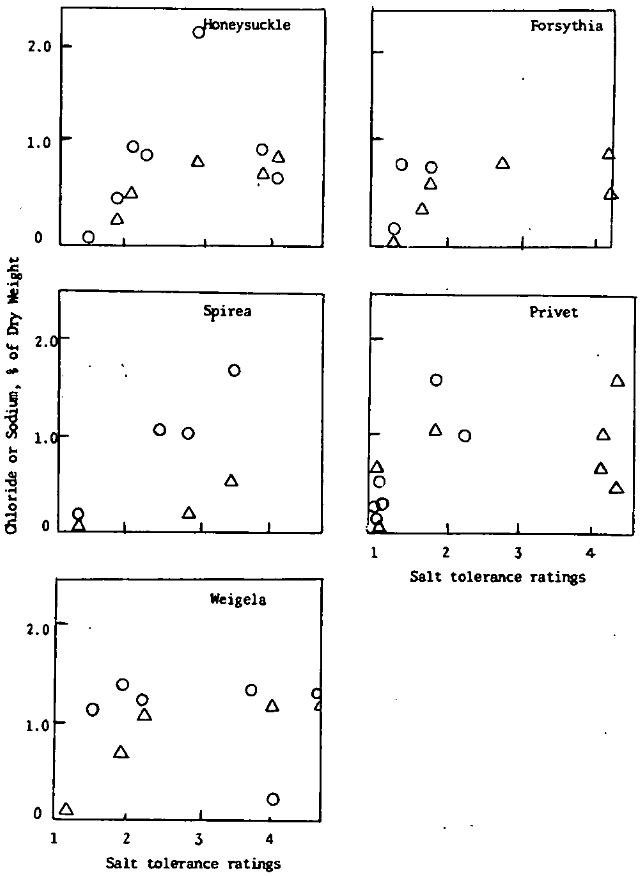

Figure E-3. Relationship between the tolerance to deicing salts of various deciduous shrubs and the chloride and sodium contents of their leaves (June 1967). Chloride O. Sodium Δ.

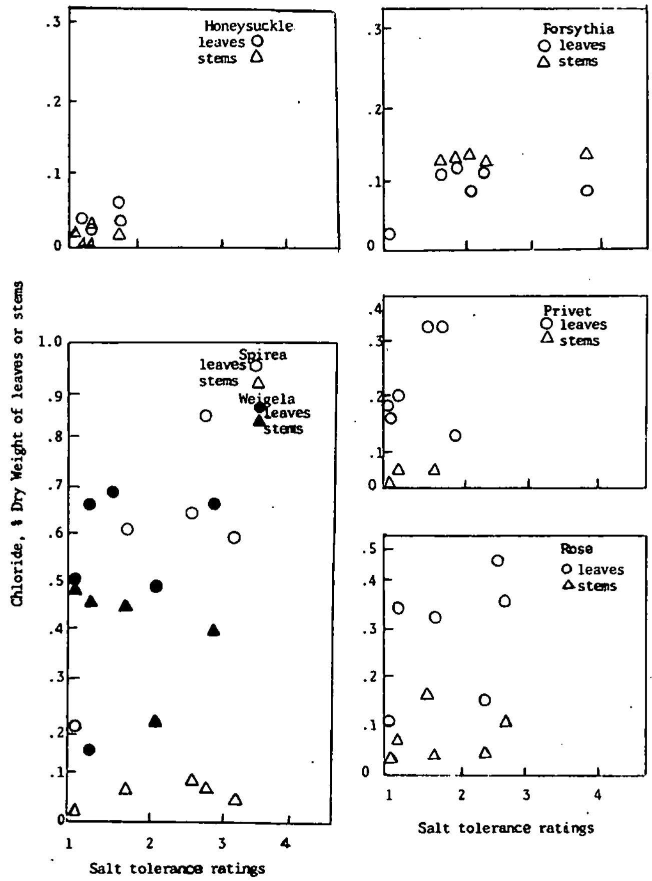

Figure E-4. Relationship between the chloride content of the leaves and stems of various deciduous shrubs and the degree of salt injury to the shrubs (August 1968).

centage of chloride in leaves and stems and the degree of injury for the salt treatments applied the second winter (Fig. E-4). The percentage of chloride or sodium in the plants is plotted against the salt tolerance rating values that reflect the degree of leaf burn, defoliation, and limb deterioration of the shrubs. Data for June 1967, following application of deicing salts the previous winter, show that the percentages of chloride and sodium in leaves were generally related to the degree of salt injury. It was observed that the concentrations of chloride and sodium increased to a maximum and then decreased as plant injury became severe. In general, this pattern of salt uptake occurred for all shrubs; however, salt injury varied with individual species. Data collected after the second winter of salt treat-

TABLE E-6

EXTREME VALUES OF SALT-TOLERANCE RATINGS OF DECIDUOUS SHRUBS AND EXTREME PERCENTAGE VALUES OF CHLORIDE, SODIUM, AND CALCIUM IN LEAVES AND STEMS (AUGUST, 1968)

SPECIES	SALT-TOLERANCE RATINGS [b]		LEAVES (% DRY WEIGHT)						STEMS (% DRY WEIGHT)					
			CHLORIDE		SODIUM		CALCIUM		CHLORIDE		SODIUM		CALCIUM	
	LOW	HIGH	LOW	HIGH	LOW	HIGH	LOW	HIGH	LOW	HIGH	LOW	HIGH	LOW	HIGH
Honeysuckle	1.3	1.7	0.024	0.060	0.001	0.004	0.57	0.96	0.008	0.026	0.001	0.006	0.08	0.09
Forsythia	1.0	2.4	0.013	0.112	0.001	0.007	0.33	0.66	0.041	0.134	0.002	0.028	0.05	0.12
Spirea	1.1	3.3	0.193	0.846	0.001	0.002	0.35	0.50	0.019	0.082	0.001	0.003	0.15	0.26
Privet	1.1	2.0	0.108	0.332	0.001	0.028	0.44	0.56	0.035	0.066	0.004	0.036	0.04	0.07
Weigela	1.1	3.0	0.142	0.684	0.005	0.013	0.38	0.43	0.094	0.484	0.009	0.024	0.02	0.08
Rose	1.1	2.7	0.108	0.454	0.003	0.009	0.31	0.98	0.032	0.164	0.002	0.003	0.33	0.45

[a] The high and low values for the chemical components should not be associated with the high and low values in salt-tolerance ratings.
[b] The salt-tolerance ratings for some of the salt-susceptible species were lower than given, but the shrubs were dead and could not be sampled for chemical analysis.

ment showed sharp species variations (Fig. E-4). The chloride content of the leaves and stems of honeysuckle was very low, and little injury occurred. Privet contained variable but significant amounts of chloride yet showed no injury. Spirea and weigela maintained relatively high chloride contents, while forsythia was low in percentage of chloride; however, all three of these shrubs were severely injured because of chloride absorption.

A summary of the association between salt content and the degree of salt injury for all species the first year illustrates the broad and variable relationship (Figs. E-5 and E-6). The values are much higher for chloride than for sodium and data must be associated with individual species and degree of injury. The species by salt treatment interactions were highly significant. When the chloride content of all species was plotted for the second-year data, there was more variation and also the chlorides made up a much lower percentage of the tissue than for the first year (Figs. E-7 and E-8). The stems were low in chlorides as compared with the leaves. The sodium content of the leaves and stems of the shrubs was very low during the second year, and the low amounts absorbed were near normal and could not be associated with salt injury (Table E-6) Calcium content varied sharply, but it was not associated with tolerance of, or susceptibility to, deicing salt ions.

The concentration of chloride and sodium in plants was high and caused much injury the first year. During the

TABLE E-7

CHLORIDE, SODIUM, AND CALCIUM CONTENTS OF DECIDUOUS SHRUBS (WARSAW, VA., AUGUST 1969)

		SALT TREATMENT (LB/ACRE)			
		1968–69		1968	
SPECIES	CHECK	NaCl 3,000	$CaCl_2$ 3,000	NaCl 6,000	$CaCl_2$ 6,000
	Chloride (% dry weight)				
Honeysuckle	0.023	0.036	0.064	0.054	0.074
Forsythia	0.071	0.080	0.076	0.079	0.086
Spirea	0.197	0.788	0.926	0.663	0.895
Privet	0.199	0.205	0.493	0.288	0.453
Weigela	0.168	0.299	0.431	0.322	0.501
Rose	0.268	0.451	0.543	0.339	0.638
	Sodium (% dry weight)				
Honeysuckle	0.007	0.004	0.010	0.004	0.003
Forsythia	0.002	0.003	0.003	0.003	0.004
Spirea	0.007	0.008	0.009	0.014	0.010
Privet	0.009	0.017	0.007	0.034	0.008
Weigela	0.002	0.002	0.002	0.005	0.006
Rose	0.003	0.010	0.002	0.002	0.001
	Calcium (% dry weight)				
Honeysuckle	0.88	0.77	1.03	0.67	0.89
Forsythia	0.53	0.45	0.77	0.46	0.88
Spirea	0.81	0.67	1.35	0.45	1.29
Privet	0.68	0.44	0.84	0.45	0.76
Weigela	0.62	0.53	0.67	0.43	0.67
Rose	1.01	1.13	1.10	1.01	0.80

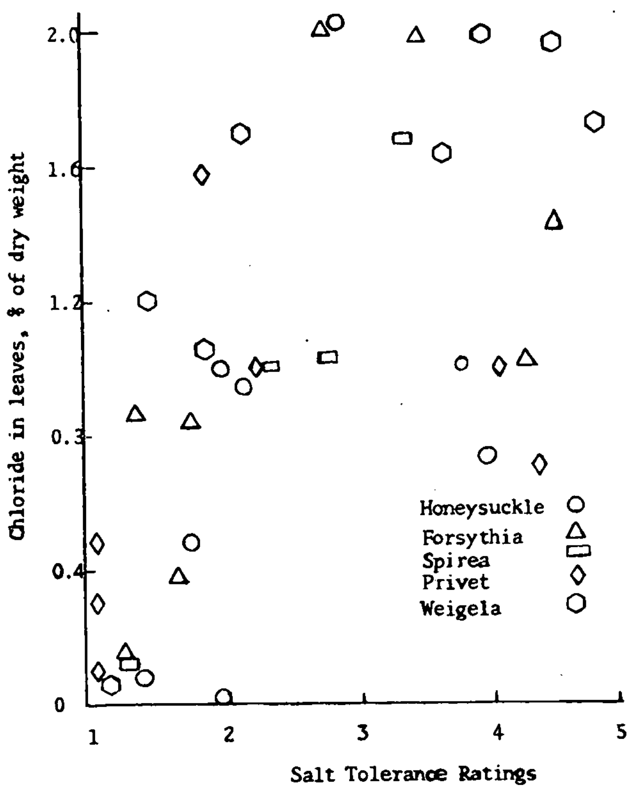

Figure E-5. Relationship between the chloride content of the leaves of various deciduous shrubs and the degree of salt injury to the shrubs (June 1967).

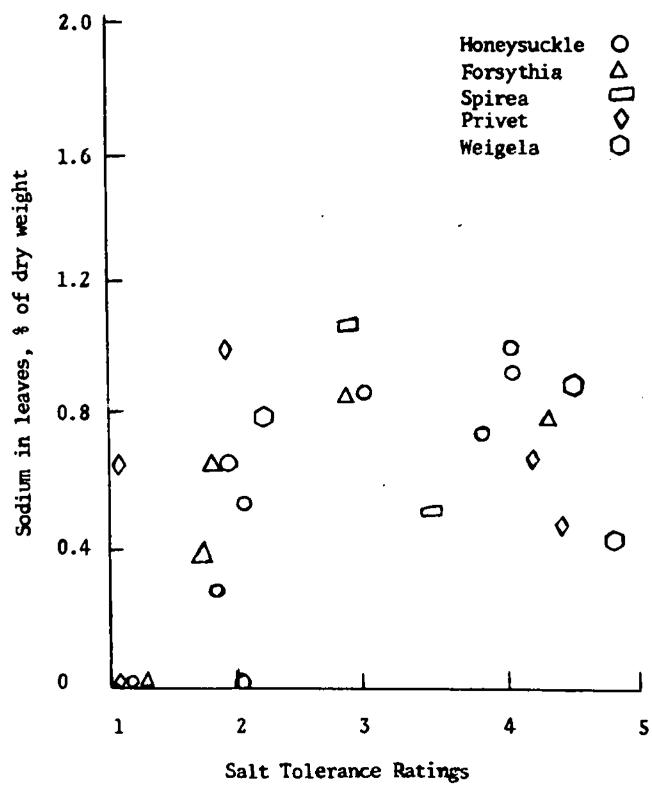

Figure E-6. Relationship between the sodium content of the leaves of various deciduous shrubs and the degree of salt injury to the shrubs (June 1967).

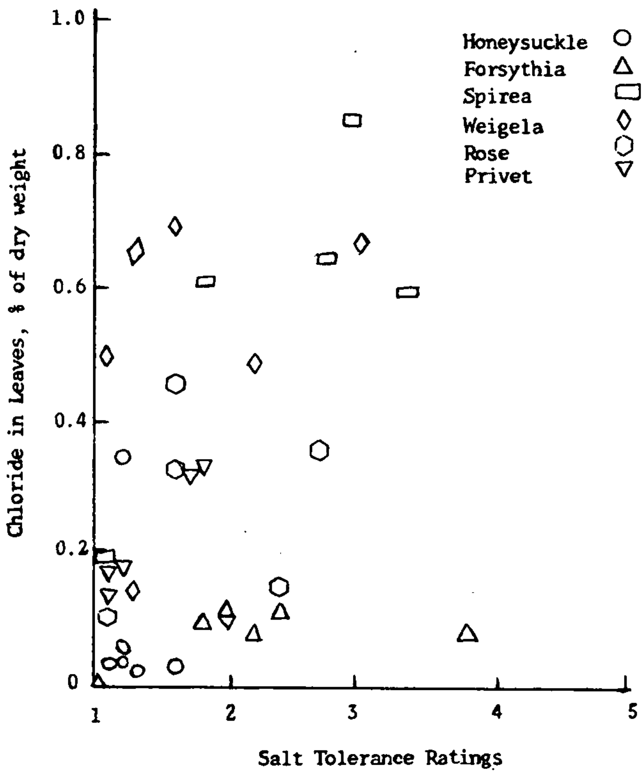

Figure E-7. Relationship between the chloride content of the leaves of various deciduous shrubs and the degree of salt injury to the shrubs (August 1968).

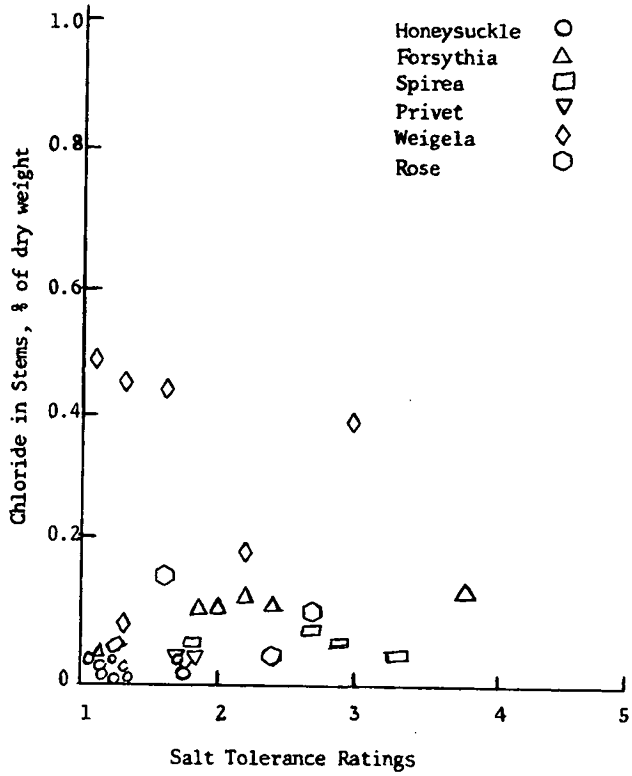

Figure E-8. Relationship between the chloride content of the stems of various deciduous shrubs and the degree of salt injury to the shrubs (August 1968).

second year the chloride was lower than for the first year and sodium absorption was low, yet injury was severe. These relationships were previously mentioned (Figs. E-1 and E-2), when the highest salt concentrations in the soil resulted in severe plant injury but also resulted in reductions in chloride and sodium in the plants. The association between plant composition and salt injury indicates that severely injured plants may lose their physiological capacity to maintain high salt contents in the stems and leaves. Losses of chloride and sodium from these plants may also occur due to rains, which leach these and other ions from injured tissues. Similar reductions in percentage of chloride and sodium contents in deciduous tree leaves occurred with the most severe salt injury (*1*).

The chloride content of leaves of shrubs measured the third year again was higher for check treatments but varied with species (Table E-7). Also, slightly higher concentrations of chloride occurred with $CaCl_2$ than for NaCl. Percentage of sodium in the leaves of shrubs was very low. Calcium percentage appeared to be normal, however calcium content was usually increased when the $CaCl_2$ was applied. Neither calcium nor sodium contents could be associated with salt injury of shrubs.

The application of 3,000 lb per acre of NaCl in split applications during January and February affected the chloride content of the stems of plants as early as March, and the first spring leaves also contained a higher-than-normal level of chloride (Fig. E-9). Thus salt ions are absorbed during winter; dormancy does not mean that roots are inactive. Seasonal changes in the percentage of chloride in leaves varied greatly for species.

Sodium content was also affected by salt treatment (Fig. E-10). The sodium values were low except in the privet, which absorbed significant amounts of sodium. Shrubs at the Warsaw location contained normal low percentages of sodium although during the first year, when the shrubs were small, there were significant increases in sodium content as a result of applying salts. The Blacksburg shrubs were much smaller compared with those at the Warsaw location. Perhaps this accounts for considerable sodium intake by the Blacksburg shrubs during the third year. However, in no case could sodium content in the shrubs at Blacksburg be associated with injury from salt applications.

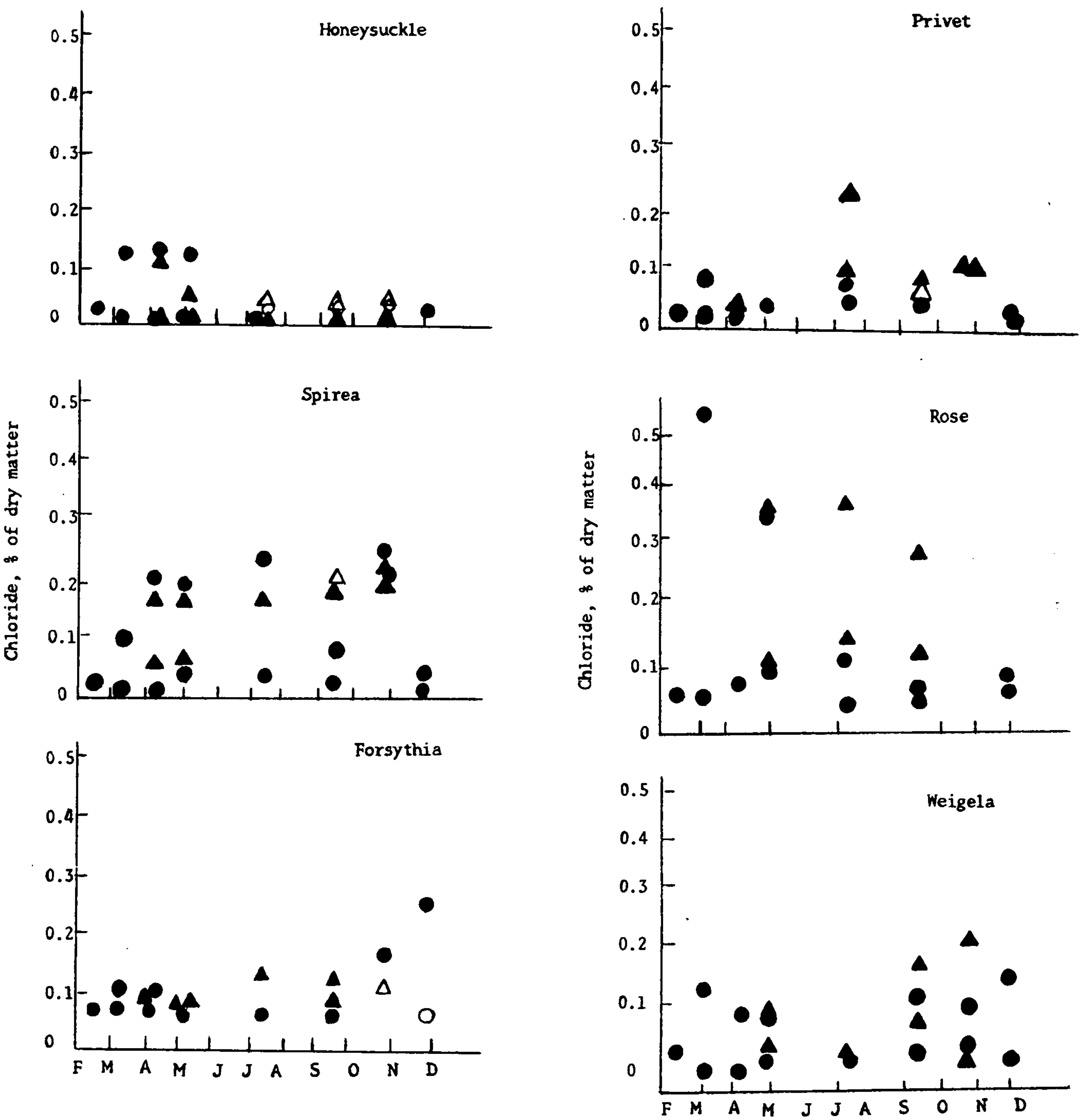

Figure E-9. Seasonal changes in the chloride content of leaves and stems of various deciduous shrubs when treated with 3,000 lb per acre of sodium chloride and when untreated (1968). Treated stems ○, leaves △. Untreated stems ●, leaves ▲.

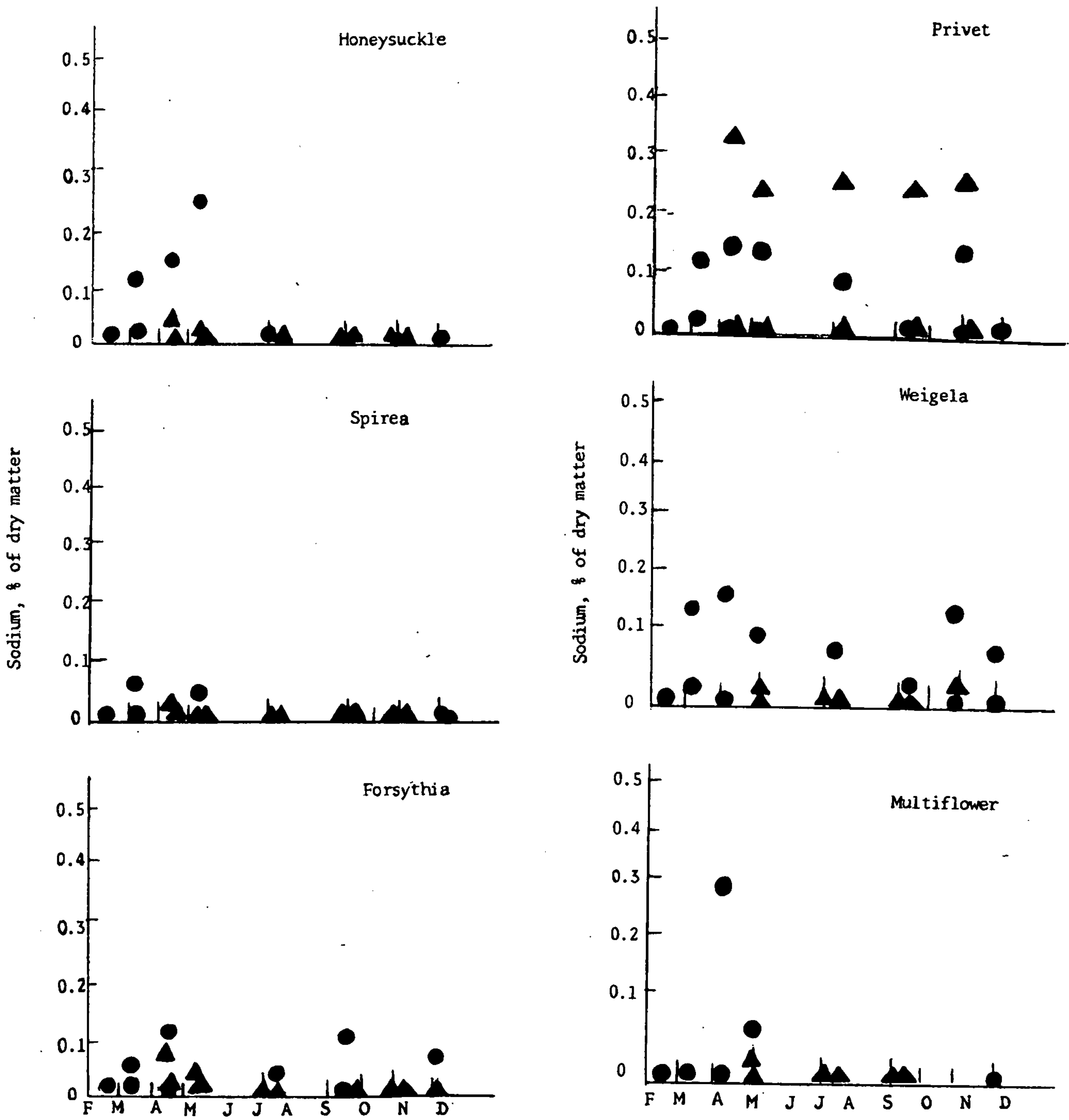

Figure E-10. Seasonal changes in the sodium content of leaves and stems of various deciduous shrubs treated with 3,000 lb per acre of sodium chloride (1968). Leaves ▲. Stems ●.

APPENDIX F

EFFECTS OF DEICING SALTS ON TISSUE COMPOSITION OF EVERGREEN TREES AND SHRUBS

Field experiments described in Appendix C provide the basis for this part of the study.

Evergreen species differed significantly in salt tolerance levels, although as the increments of deicing salts increased so did the incidence of plant injury.

Tissue samples collected in August 1968 were subjected to the laboratory procedures to determine chloride and sodium concentrations, which are given in Table F-1. Missing values in the table indicate that plants were dead in all three replications and certain other values represent only one of the three replications that had live plants for sampling. The chloride content of all species was significantly increased by salt applications. The percentage of chloride in the tissues varied with the plant species and increased as more NaCl was applied. Chloride absorption was high with both sodium and calcium salts. The plants severely injured by salts (white pine, Norway spruce, and hemlock) generally absorbed seven to fifteen times more chloride than untreated plants.

Sodium absorption by plants was much lower than that of chloride. Only the Adam's needle and possibly Norway spruce and hemlock absorbed more sodium than the check plots (Table F-1). All other species showed low and normal sodium content, even when high rates of salts were applied.

The salt-sensitive species did not survive the high salt treatments applied the first winter (Fig. F-1). However, the tolerant plant species were sampled and analyzed in August 1968. No salts were applied to these plants after the first winter. The results reported (Table F-2) are similar to the data discussed previously. Chloride content was again related to the amount of salt applied to which species. Sodium uptake was generally low except that Norway spruce, hemlock, and Adam's needle absorbed considerable amounts. The calcium content of the plants was generally a little lower for the NaCl than the $CaCl_2$ treatment.

The relationship between salt uptake and plant injury is shown by plotting the percentage of chloride and sodium against the salt tolerance rating values (Fig. F-2). The three salt-sensitive species—white pine, Norway spruce, and hemlock—showed positive relationships between chloride uptake and plant injury; increases in chloride concentrations in plant tissue were generally associated with increased degrees of plant injury. There was much variation in chloride content of plants; severe salt injuries with the salt-sensitive plants often had tissue that was nearly dead, where chlorides may have been lost from leaching due to

TABLE F-1

CHLORIDE AND SODIUM CONTENTS OF EVERGREEN TREES AND SHRUBS (WARSAW, VA., AUGUST 1968)

		SALT TREATMENT (LB/ACRE)				
		1967–68			1968	
		NaCl		$CaCl_2$	NaCl	$CaCl_2$
SPECIES	CHECK	1,500	3,000	1,500	3,000	3,000
Chloride (% dry weight)						
Creeping juniper	0.09	0.19	0.28	0.20	0.22	0.22
Pfitzer juniper	0.07	0.12	0.16	0.15	0.13	0.15
Adam's needle	0.12	0.42	0.96	0.50	0.21	0.18
White pine	0.04	0.55	0.51	0.41	0.50	0.62
Norway spruce	0.04	—[a]	0.29	—[a]	0.46	0.29
Canadian hemlock	0.04	—[a]	—[a]	—[a]	0.31[b]	0.43
Sodium (% dry weight)						
Creeping juniper	0.004	0.057	0.098	0.004	0.068	0.024
Pfitzer juniper	0.006	0.013	0.019	0.006	0.024	0.003
Adam's needle	0.004	0.149	0.410	0.012	0.116	0.003
White pine	0.005	0.028	0.091	0.004	0.003	0.057
Norway spruce	0.003	—[a]	0.110	—[a]	0.205	0.011
Canadian hemlock	0.006	—[a]	—[a]	—[a]	0.170[b]	0.010

[a] All plants died.
[b] Some plants in one of three replications survived.

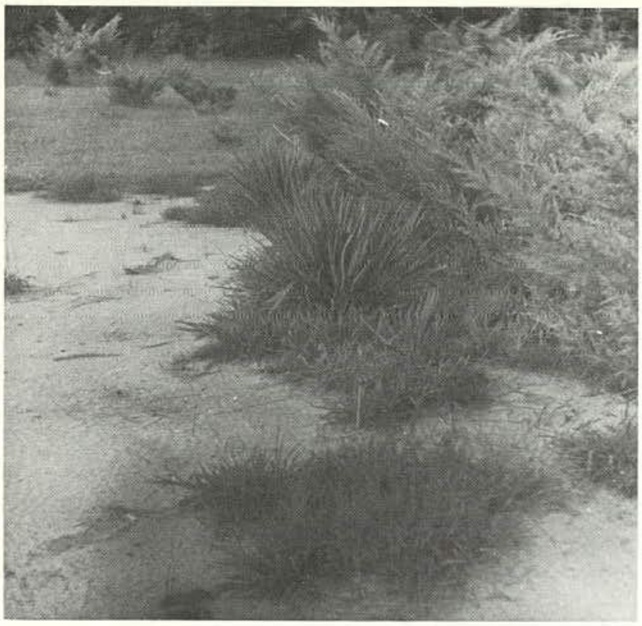

Figure F-1. Field plots illustrating the salt tolerance of creeping juniper, Pfitzer juniper, and Adam's needle. The salt-susceptible white pine, Norway spruce, and hemlock (and grass) were killed.

TABLE F-2

CHLORIDE, SODIUM, AND CALCIUM CONTENTS OF EVERGREEN TREES AND SHRUBS THAT SURVIVED HIGH SALT TREATMENTS APPLIED IN WINTER OF 1966–67 (WARSAW, VA., AUGUST 1968)

		SALT TREATMENT (LB/ACRE)			
		NaCl			$CaCl_2$
SPECIES	CHECK	6,000	8,000	12,000	6,000
	Chloride (% dry tissue)				
Creeping juniper	0.09	0.17	—	0.32	0.21
Pfitzer juniper	0.07	0.12	0.12	0.18	0.13
Adam's needle	0.12	1.44	0.94	0.91	0.40
	Sodium (% dry tissue)				
Creeping juniper	0.004	0.070	—	0.098	0.004
Pfitzer juniper	0.006	0.020	0.014	0.017	0.003
Adam's needle	0.004	0.200	0.330	0.380	0.007
	Calcium (% dry tissue)				
Creeping juniper	0.57	0.41	—	0.23	0.58
Pfitzer juniper	0.32	0.22	0.19	0.27	0.37
Adam's needle	0.21	0.13	0.49	0.37	0.38

TABLE F-3

CHLORIDE, SODIUM, AND CALCIUM CONTENTS OF EVERGREEN TREES AND SHRUBS (WARSAW, VA., AUGUST 1969)

		SALT TREATMENT (LB/ACRE)			
		1968–69		1969	
SPECIES	CHECK	NaCl 3,000	$CaCl_2$ 3,000	NaCl 6,000	$CaCl_2$ 6,000
	Chloride (% dry tissue)				
Creeping juniper	0.078	0.138	0.197	0.207	0.191
Pfitzer juniper	0.066	0.104	0.116	0.116	0.134
Adam's needle	0.146	0.397	0.305	0.406	0.335
White pine	0.031	0.437	0.501	0.698	0.788
Norway spruce	0.041	0.417	0.214	0.589	0.411
Canadian hemlock	0.034	0.536	0.640	0.607	0.531
	Sodium (% of dry tissue)				
Creeping juniper	0.001	0.023	0.003	0.156	0.001
Pfitzer juniper	0.002	0.033	0.002	0.039	0.005
Adam's needle	0.008	0.096	0.011	0.173	0.003
White pine	0.004	0.056	0.004	0.010	0.008
Norway spruce	0.003	0.217	0.008	0.405	0.003
Canadian hemlock	0.025	0.432	0.013	0.295	0.004
	Calcium (% of dry tissue)				
Creeping juniper	0.59	0.65	0.74	0.69	0.73
Pfitzer juniper	0.49	0.45	0.65	0.42	0.51
Adam's needle	0.48	0.55	0.46	0.52	0.58
White pine	0.16	0.14	0.23	0.11	0.27
Norway spruce	0.32	0.18	0.33	0.16	0.35
Canadian hemlock	0.20	0.18	0.28	0.28	0.27

ruptured cells. Sodium concentration was much lower than the chloride; however, sodium was often found to increase in plants. The tolerant plants—Pfitzer juniper, creeping juniper, and Adam's needle—did not generally show relationships between injury and salt content of tissue as for the less-tolerant species.

Salts were applied for two winters, 1968-69 and in 1969 only, on other plots with the plant species to study the salt effects on older, better-established plants. Tissue samples collected in August 1969 after the third-winter salt treatments again showed the marked effects of deicing salts on the chloride content of the plants (Table F-3). White pine, Norway spruce, and hemlock—the plants most severely injured—contained higher amounts of chloride than the tolerant species. Sodium values were also relatively high for Adam's needle, Norway spruce, and hemlock. Calcium values were not significantly affected.

The sodium and chloride absorption by evergreen trees and shrubs when treated with 1500 lb per acre of NaCl during two years is shown in Figures F-3 and F-4. This deicing salt increased the chloride content substantially during the subsequent year. However, the amounts of chloride absorbed were low for the junipers and declined very sharply one year after applying the salts. As compared with check treatments, the chlorides were high and remained high for the white pine and Norway spruce. These latter two species, along with hemlock, that were severely injured by deicing salts had absorbed very high amounts of chlorides as compared to the trees without salt (Fig. F-3). It is important to note that the salt-tolerant junipers were highest in chloride in March and then declined during the rest of the year. Conversely, the salt concentrations in plant tissues of the three susceptible species increased during the summer and values remained high during fall and winter one year after applying salts. Thus, susceptible species absorbed large amounts of chlorides over prolonged periods of time as compared with the tolerant species. The sodium content of these plants treated with NaCl was higher than for the untreated ones, but it was variable (Fig. F-4). The salt-tolerant juniper evergreens absorbed low amounts of sodium and most of the absorption occurred during spring; during the later summer-winter season, sodium content was similar to that for trees without salt. Norway spruce absorbed more sodium throughout the year than the other evergreens. White pine and hemlock were intermediate as compared with other species in salt absorption.

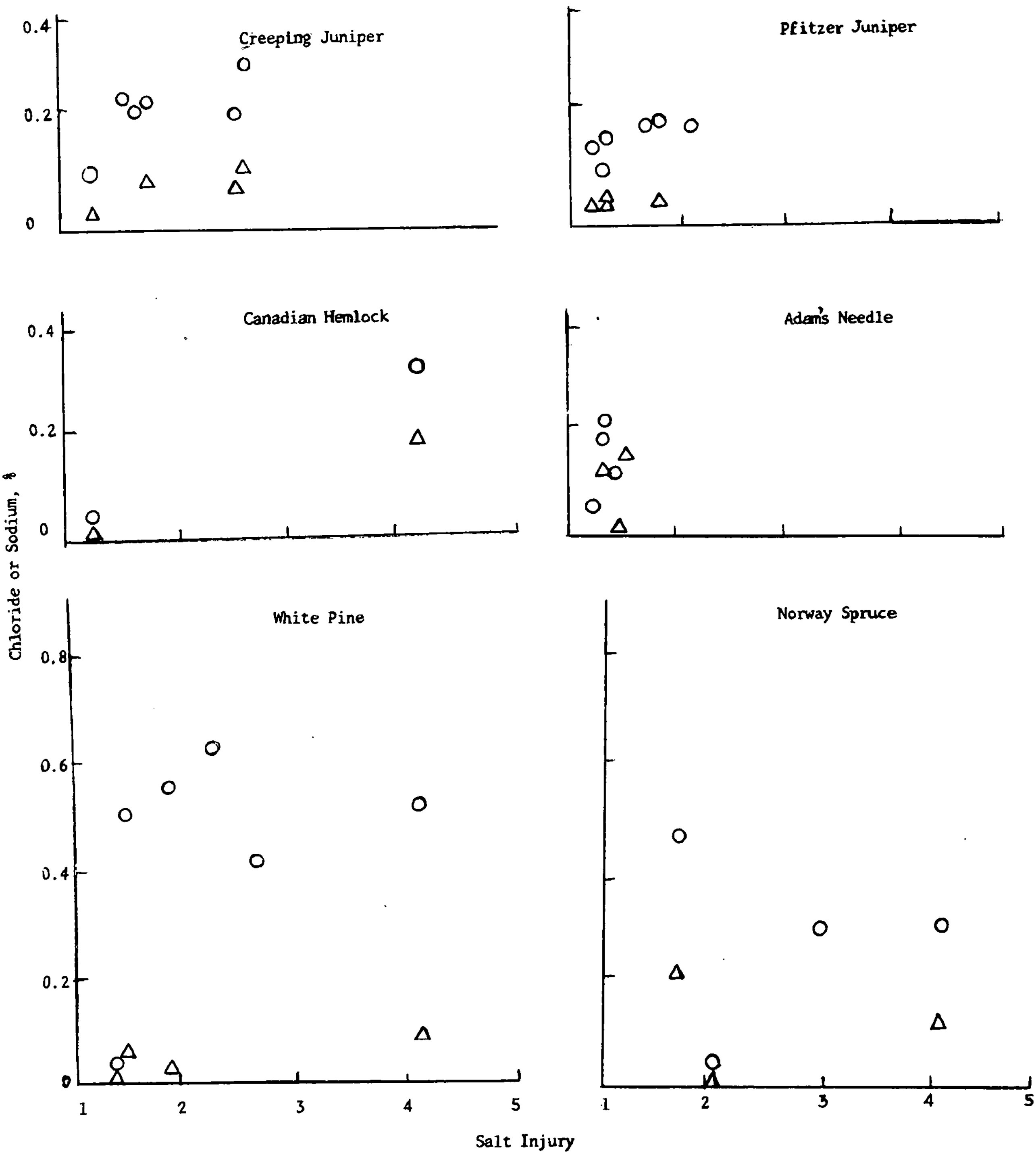

Figure F-2. Relationship between the chloride and sodium contents in evergreen plant tissues and the degree of salt injury to the plants (August 1968). ○ Chloride. △ Sodium.

It is apparent that chlorides are the primary ion causing injury to evergreens. Species displaying little injury to salt absorbed much less chloride than the evergreens susceptible to salt injury.

The data suggest that salt-tolerant species can be selected for planting along highways where deicing salts are used. Planting trees at distances from highways would reduce the injury from deicing salts.

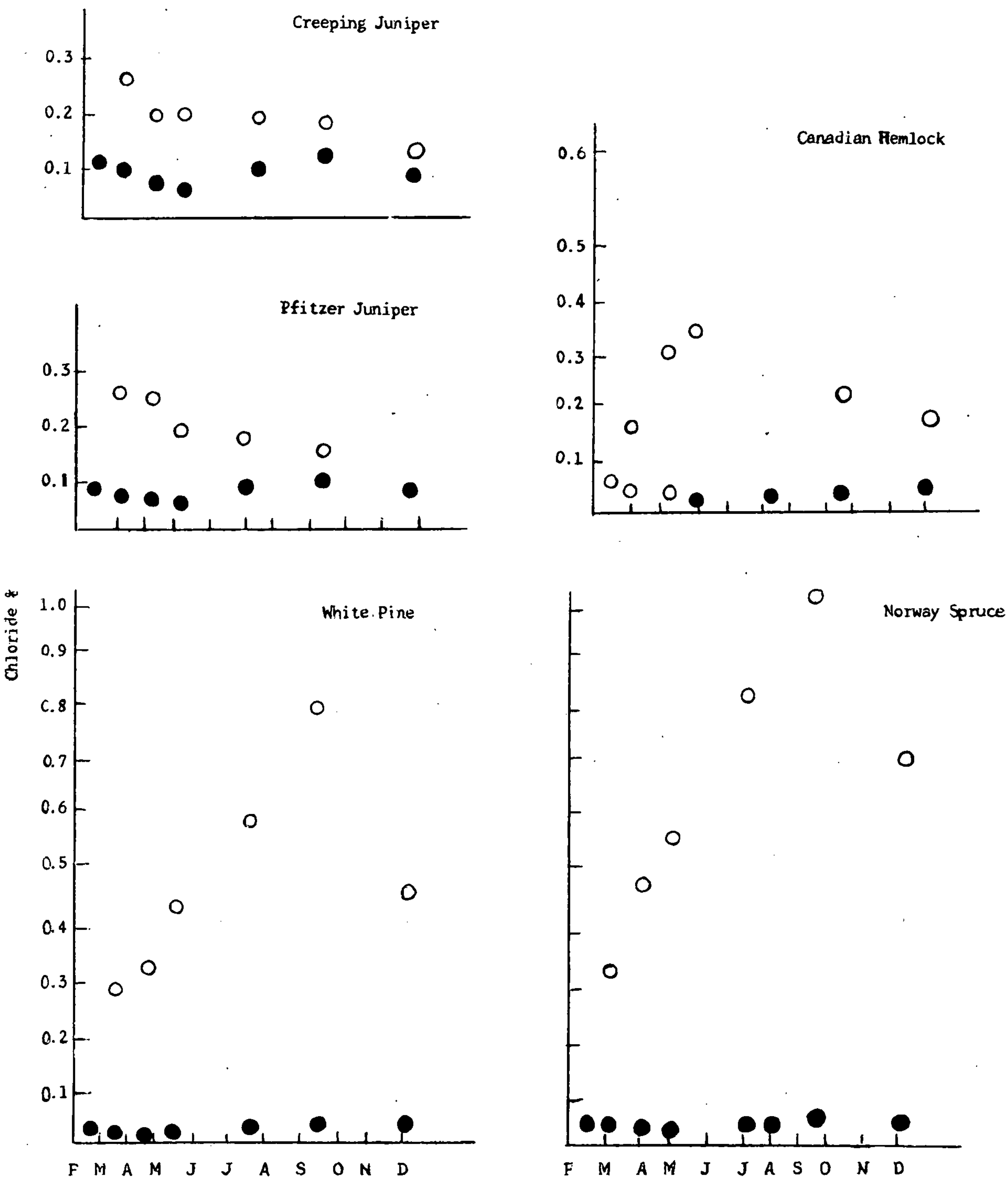

Figure F-3. Chloride absorption for various evergreen shrubs and trees during the 1969 season.
○ Untreated. ● Treated.

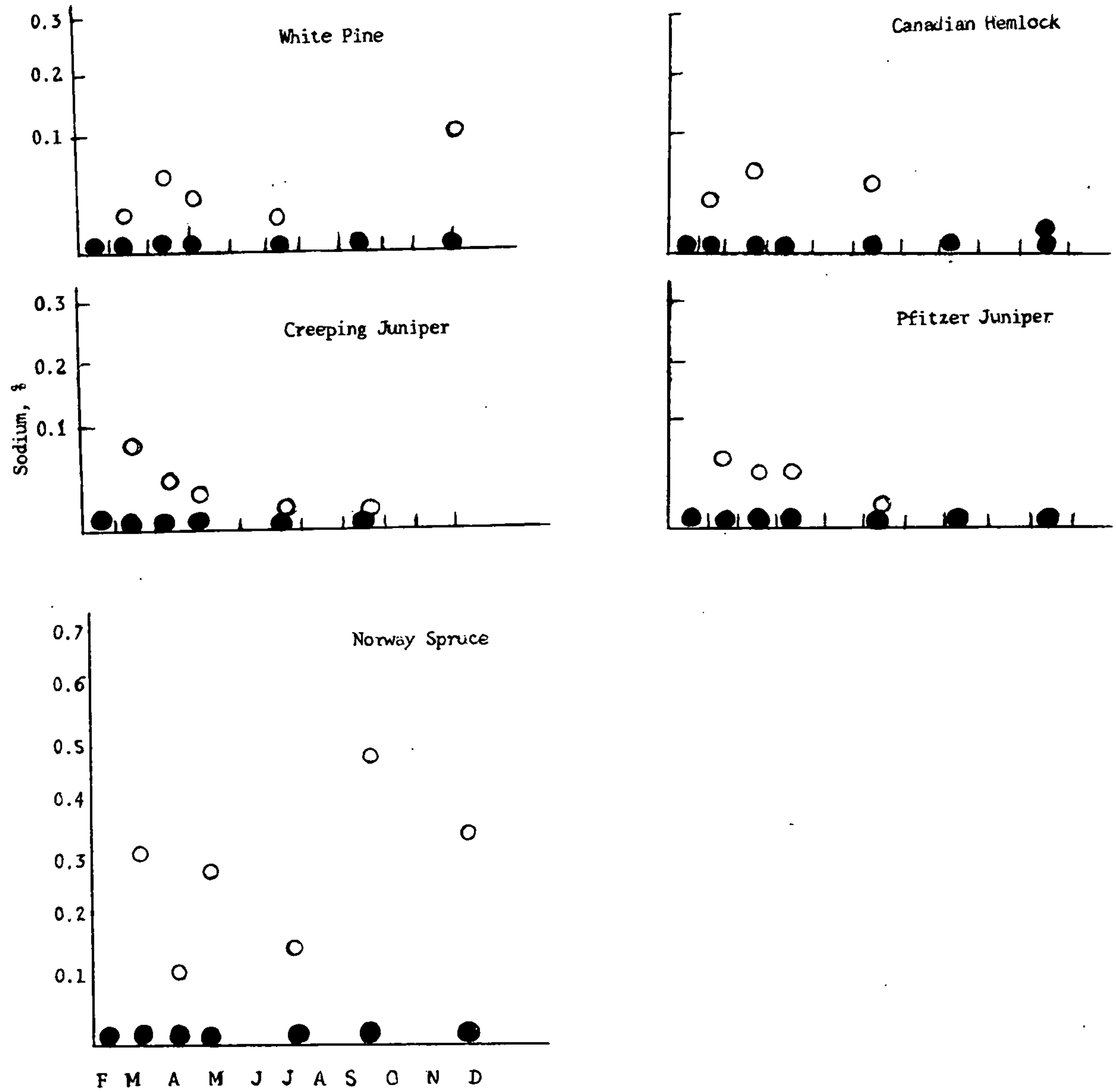

Figure F-4. Sodium absorption for various evergreen shrubs and trees during the 1969 season. ○ Untreated. ● Treated.

APPENDIX G

SODIUM CHLORIDE UPTAKE AND DISTRIBUTION IN GRASSES AS INFLUENCED BY FERTILITY INTERACTION AND COMPLEMENTARY ION COMPETITION

The mechanisms of sodium chloride uptake and distribution within plants differ among grass species. Apart from osmotic effects, the susceptibility or tolerance of grasses to salt is suspected to depend on the uptake, distribution, and accumulation of sodium and chloride that result in an ionic imbalance. Ionic imbalances can be caused by salinity-fertility interactions.

Elzam et al. (*20*), studying chloride absorption by roots, distinguished between a high-affinity transport system operating below 1.0 meq per litre of chloride and a number of low-affinity transport systems operating above this concentration. Luttage and Latties (*21*) reported that chloride transport to the shoot of corn seedlings is either by the high-affinity mechanism at lower concentrations or by diffusion across the plasma membrane. Diffusion as a mechanism of chloride movement was also reported by Torii and Latties (*22*).

The cell membrane situated adjacent to the cell wall performs the vital role of regulating the passage of nutrients in and out of the cell. Ordinary diffusion of chloride across the cell membrane is not very likely. On the other hand, it is more likely that an active mechanism controlled by live processes within the plant is operative for the transport of chloride across the cell membrane. Regardless of the mechanism, an increase in concentrations of complementary anions in the absorbing medium may result in anion competition causing a reduction in chloride uptake by roots.

The purpose of these investigations was to determine the relationships among rates of application of sodium chloride on the absorption of sodium and chloride by grasses under fairly high fertility levels, their effect on growth, and the effect of complementary anions and cations in the rooting medium on sodium and chloride absorption.

RESEARCH APPROACH

A preliminary experiment with Kentucky 31 fescue (*Festuca arundinacea*) was seeded in April 1966 at Blacksburg to establish the relationship between sodium chloride absorption and rate of application of this salt applied in the form of commercial rock salt. A basic application of 60 lb of nitrogen, 26 lb of phosphorus, and 50 lb of potassium was applied at seeding. An additional 50 lb of nitrogen was applied in August. NaCl was applied at six different rates October 20, 1966, and again November 4, 1966. Tissues were collected on three dates: October 24; November 4 before the second treatment; and November 18, 1966. The tissues were washed to remove surface salt, dried, and analyzed for sodium and chloride.

The response of grasses to sodium chloride treatment and nitrogen application was studied in a field experiment at Warsaw in 1968. Bromegrass (*Bromus intermis Leyss*), red fescue (*Festuca rubra*), Kentucky bluegrass (*Poa pratense*), and Kentucky 31 fescue (*Festuca arundinacea*) were seeded in April 1966 and maintained under medium fertility levels until treatments were applied in 1968. Salt treatments consisted of four levels of sodium chloride—0, 2, 4, and 6 tons per acre—applied in rates of two tons each during January, February, and March 1968. A nitrogen treatment at 50 lb of nitrogen per acre was imposed on the salt treatments in a split-plot design during April. The plants were harvested in June and analyzed for sodium and chloride.

A greenhouse experiment on tolerance with Kentucky 31 fescue (*Festuca arundinacea*), red fescue (*Festuca rubra*), and Kentucky bluegrass (*Poa pratense*) under both high- and low-fertility environments was conducted in sand culture during the winter of 1969. Six weeks after seeding, the grasses were clipped to a uniform height and NaCl solutions 0, 1,000, 2,000, and 4,000 ppm were applied. These salt solutions were used for watering for a period of 17 days at 100 ml per day. Tops were then harvested and roots carefully removed by washing several times to separate from the sand. Their weights were recorded.

The interaction of fertility treatments to sodium chloride uptake by grasses was studied in the greenhouse in the fall of 1966. Kentucky 31 fescue was used as the test plant on a Groseclose soil. The experiment contained four levels of nitrogen at 15, 100, 200, and 400 lb per acre, one level of phosphorus at 58 lb per acre, and four levels of potassium at 0, 35, 104, and 208 lb per acre. Sodium chloride solutions were applied to each of the fertility treatments at the rate of 2 tons per acre after fescue was 4 in. tall. A randomized complete block design with four replications was used for the study. The grasses were harvested on the sixth day and yields recorded. After drying, the tissues were analyzed for sodium, calcium, magnesium, potassium, and chloride.

The effect of complementary ions in the rooting medium on sodium and chloride absorption was studied in the greenhouse in summer 1969. Plastic pots were lined with polyethylene bags and filled with 2 kg of a Groseclose silt loam. The soil was medium in phosphorus and potassium and fairly high in exchangeable bases. The clay fraction contained partially chloritized vermiculite, kaolinite, mica, geothite, and quartz. Although kaolinite was most abundant, enough other minerals were present to prevent calling the clay fraction kaolinite. The soil received a basal application of 20 lb per acre each of nitrogen, phosphorus, and potassium. A corn hybrid (Muncy Chief) was seeded and thinned after germination to four plants per pot. The moisture content of the soil was maintained with distilled water at 75 percent by weight of the field capacity. Eight chloride treatments with or without sulfate, phosphate, and nitrate were applied. NaCl was used as the source of chloride; and equivalent amounts of sulfate, phosphate, and nitrate were applied as sodium, calcium, or potassium. This way chloride concentration was kept constant at 200 lb per acre; sodium concentration was varied from 143 to 410 lb per acre by using equivalent amounts of sulfate, phosphate, and nitrate as sodium. Also sodium and chloride concentrations were kept constant at 143 and 200 lb per acre, respectively, through the use of calcium and potassium sources. A complete block design with five replications was used. Salt treatments were initiated 10 days after germination. The plants were harvested at the ground level 10 days after the salt treatment. Roots were removed by washing with water. The tissues were dried and analyzed by standard laboratory procedures.

Salt injury and vigor ratings were made before harvest to determine the salt effect on the plant. A numerical scale from 1 to 10 was established. No. 1 indicated no injury and the degree of injury progressed up the scale to No. 10, which indicated severe injury. For vigor rating, on the other hand, 1 indicated complete loss of vigor while 10 indicated full vigor.

RESULTS AND DISCUSSION

Effect of Rates of Application of Sodium Chloride on the Uptake of Sodium and Chloride by Grasses

It is evident (Table G-1) that an increase in the percentage of sodium contained in the fescue tops was commensurate with an increase in the rate of application of sodium chloride. This was true for each harvest. The chloride content of the tissues also increased with increasing application of sodium chloride. However, the chloride content of the tissues was several times higher than the corresponding sodium content. An average of the three cuttings showed that the chloride content for the check treatment was 14 times higher than the corresponding sodium content. It has been reported (*2*) that certain plants accumulate chloride from acid soils more rapidly than others and that accumulation of chloride was more rapid from calcium chloride than sodium chloride.

A simple linear regression analysis was computed for each cutting to establish the relationship between sodium and chloride contents in tissues having had sodium chloride applied. A highly significant relationship existed (Table G-2) between sodium chloride treatments and sodium and chloride contents in tissues. The data indicate that increasing concentrations of sodium and chloride applied to grasses increase the sodium and chloride contents in tissues. However, their increase in tissues may be due to salt concentration, reduced plant growth, or both.

TABLE G-1

EFFECT OF RATES OF APPLICATION OF SODIUM CHLORIDE ON THE CONTENTS OF SODIUM AND CHLORIDE IN KENTUCKY 31 FESCUE TOPS

NACL TREATMENT (TONS/ ACRE)	AVERAGE CONTENTS IN CUTTINGS PER HARVEST					
	SODIUM (% DRY WEIGHT)			CHLORIDE (% DRY WEIGHT)		
	1	2	3	1	2	3
0.00	0.07	0.07	0.02	0.93	1.34	0.97
0.25	0.47	0.42	0.31	1.60	1.66	1.46
0.50	0.82	0.59	0.59	2.38	1.94	1.57
1.00	1.58	1.16	1.08	3.04	2.90	2.06
2.00	2.00	2.10	1.58	4.12	3.76	2.59
4.00	3.20	3.20	2.68	5.33	5.55	4.16

TABLE G-2

LINEAR CORRELATION COEFFICIENTS FOR SODIUM AND CHLORIDE ABSORPTION BY KENTUCKY 31 FESCUE

CUTTING DATE	LINEAR CORRELATION COEFFICIENT	
	SODIUM	CHLORIDE
10–24–66	0.944[a]	0.911[a]
11– 4–66	0.961[a]	0.932[a]
11–18–66	0.799[a]	0.949[a]

[a] Indicates significance at 1-percent level.

Effect of Sodium Chloride Treatments on Yield and on Sodium and Chloride Contents of Grasses as Influenced by Fertility Treatments

Sodium chloride treatments depressed the yield of all four grass species (Table G-3). Increased rates of sodium chloride caused a corresponding decrease in the yield of the grass. The reduction in yield due to sodium chloride was in the order of Kentucky bluegrass > bromegrass > red fescue > Kentucky 31 fescue. Nitrogen treatment tended to minimize the yield depression, which was due to sodium chloride. The increase in yield caused by adding nitrogen was influenced more by species than by the salt treatments themselves. At the rate of 50 lb of nitrogen per acre, Kentucky 31 fescue maintained reasonable ground cover even at 4 and 6 tons of sodium chloride per acre.

TABLE G-3

EFFECT OF SODIUM CHLORIDE AND NITROGEN ON THE YIELDS OF FOUR GRASS SPECIES AS WELL AS THE PERCENTAGE ABSORPTION OF SODIUM AND CHLORIDE BY THE GRASSES

TREATMENT (TONS/ACRE)	BROMEGRASS			RED FESCUE			KENTUCKY BLUEGRASS			KENTUCKY 31 FESCUE		
	YIELD	Na	Cl	YIELD	Na	Cl	YIELD	Na	Cl	YIELD	Na	Cl
	(G/ PLOT)	(% DRY WEIGHT OF TOPS)		(G/ PLOT)	(% DRY WEIGHT OF TOPS)		(G/ PLOT)	(% DRY WEIGHT OF TOPS)		(G/ PLOT)	(% DRY WEIGHT OF TOPS)	
Check	460	0.01	0.45	401	0.01	0.41	312	0.01	0.35	478	0.02	0.80
Check+N[a]	527	0.01	0.58	460	0.01	0.47	338	0.01	0.59	513	0.02	1.20
$NaCl_2$	361	0.04	0.55	356	0.03	0.41	196	0.03	0.50	395	0.01	1.05
$NaCl_2$+N	399	0.03	0.63	390	0.06	0.86	220	0.03	0.52	438	0.14	1.12
$NaCl_4$	180	0.04	0.60	147	0.03	0.53	100	0.03	0.41	207	0.17	1.13
$NaCl_4$+N	225	0.05	0.81	177	0.05	0.70	144	0.09	1.15	260	0.03	1.58
$NaCl_6$	100	0.11	0.89	96	0.07	0.55	82	0.08	0.97	194	0.24	1.02
$NaCl_6$+N	150	0.07	0.89	131	0.07	0.77	100	0.07	0.81	238	0.22	1.72

[a] N, nitrogen.

The application of sodium chloride during winter months significantly increased the sodium and chloride contents of all grass species. Invariably nitrogen increased the levels of sodium and chloride in tissues, perhaps due to increased metabolism. Kentucky 31 fescue tissues contained higher amounts of sodium and chloride than those of the other species. Tall fescue apparently seems to tolerate greater amounts of sodium and chloride.

Additional greenhouse studies on the same grass species showed that 1,000-ppm NaCl treatment increased the weights of tops and roots of Kentucky 31 fescue and Kentucky bluegrass at the high fertility level and decreased the yields at the low fertility level (Table G-4). Higher rates of NaCl caused a reduction in the yield of tops for all grasses at both fertility levels. However, the reduction in yield for Kentucky 31 fescue was less than that for red fescue and Kentucky bluegrass. Under high fertility levels with 4 tons of NaCl per acre, the reduction in yield was only 8 to 10 percent for Kentucky 31 fescue and 30 to 50 percent for other grasses. Generally, the reduction in yield of tops was more apparent than that of roots. Leaf tip burns were more noticeable for Kentucky bluegrass and red fescue at all rates of NaCl.

A second field experiment with Kentucky 31 fescue (Table G-5) indicated the effects of potassium and nitrogen on uptake of sodium and chloride. Increased rates of potassium decreased the uptake of sodium, indicating a highly significant sodium-potassium interaction. It appears that sodium uptake by grasses may be minimized by increasing the availability of potassium. Higher rates of nitrogen tended to increase absorption and concentration of sodium and chloride in tissues. Added nitrogen and potassium increased the absorption of chloride and sodium but to a lesser extent than increasing only nitrogen. There was little or no change in calcium and magnesium contents from rock salt treatments.

TABLE G-4

YIELDS OF TOPS AND ROOTS OF THREE GRASSES AS INFLUENCED BY SODIUM CHLORIDE AND FERTILITY LEVELS

NACL TREATMENT (PPM)	YIELD (G/PLOT) KENTUCKY 31 FESCUE TOPS	ROOTS	RED FESCUE TOPS	ROOTS	KENTUCKY BLUEGRASS TOPS	ROOTS
High fertility:						
Check	1.66	4.24	2.22	4.43	1.95	2.28
1000	2.43	5.66	1.82	3.86	2.13	3.24
2000	1.67	3.98	1.13	3.73	1.43	2.66
4000	1.53	3.86	1.00	3.56	1.30	2.32
Low fertility:						
Check	0.72	3.39	0.52	1.06	0.44	1.81
1000	0.62	2.00	0.80	1.69	0.42	1.06
2000	0.49	1.96	0.33	1.95	0.22	1.25
4000	0.48	2.75	0.34	2.89	0.21	2.78

Effect of Complementary Ions on Growth and Development and on Sodium and Chloride Uptake by Corn Seedlings

Phosphate and nitrate salts, separately or in combination with each other and applied along with deicing salts, gave significantly higher yields of corn (Table G-6) than all other treatments. The differences in dry-matter yield of roots due to the treatments were not significant.

NaCl treatment (Table G-6, treatment No. 2) caused severe injury to plants, resulting in loss of vigor. The injury symptoms consisted of burning of tips and margins, producing a scorched appearance. Addition of sulfate as sodium sulfate improved the vigor of plants to some extent but did not decrease salt injury significantly. However, phosphate alone or a mixture of phosphate and nitrate by the use of sodium, calcium, or potassium salts (Table G-6, treatments No. 4 through 8) decreased sodium chloride injury significantly. These treatments also increased the vigor of plants. Potassium salts reduced sodium chloride injury more than calcium. The results indicated that the deleterious effect of deicing compounds on vegetation along highways can be reduced to some extent by maintaining a good soil fertility program on roadside plantings. Boyce (*18*) reported that phosphates did not cause a greater salt injury to sea oats, while nitrates did. He also reported a reduction in tolerance of oats with nitrates.

Sulfate, phosphate, and nitrate ions applied as sodium salts decreased the uptake of chloride, but not sodium, ions by corn seedlings (Table G-7). Phosphate ions were more effective than sulfate ions. Sulfate, phosphate, and nitrate ions applied as salts of calcium and potassium also decreased chloride and sodium uptake. However, potassium

TABLE G-5

EFFECT OF SODIUM CHLORIDE AT DIFFERENT FERTILITY LEVELS ON THE PERCENTAGE OF CHLORIDE, SODIUM, CALCIUM, MAGNESIUM, AND POTASSIUM CONTENTS IN KENTUCKY 31 FESCUE

TREATMENT [a] (LB/ACRE)	YIELD (% DRY WEIGHT) Cl	Na	Ca	Mg	K
60N–26P–50K	0.73	0.04	0.36	0.02	1.72
60N–26P–50K+NaCl	2.08	0.92	0.34	0.18	1.40
160N–26N–50K	0.73	0.02	0.48	0.02	1.72
160N–26P–50K+NaCl	2.55	1.18	0.38	0.18	1.62
210N–26P–50K	0.85	0.04	0.36	0.02	2.05
210N–26P–50K+NaCl	2.87	1.42	0.41	0.02	2.00
60N–26P–100K	0.72	0.02	0.40	0.18	1.75
60N–26P–100K+NaCl	2.66	1.25	0.36	0.18	1.44
60N–26P–175K	0.60	0.03	0.33	0.20	1.42
60N–26P–175K+NaCl	2.25	0.95	0.35	0.20	1.50
60N–26P–300K	0.74	0.03	0.35	0.20	1.68
60N–26P–300K+NaCl	2.20	0.95	0.29	0.20	1.49
160N–26P–100K	0.72	0.02	0.39	0.20	1.68
160N–26P–100K+NaCl	2.34	1.10	0.31	0.18	1.72
210N–26P–175K	0.88	0.04	0.39	0.20	2.20
210N–26P–175K+NaCl	2.77	1.32	0.31	0.20	2.15

[a] N, nitrogen; P, phosphorus; K, potassium.

TABLE G-6

EFFECT OF COMPLEMENTARY ANIONS IN THE ROOTING MEDIUM ON YIELD AND VIGOR OF CORN SEEDLINGS

SOIL TREATMENT		YIELD (G/PLOT)			
NO.	TYPE	TOPS	ROOT	INJURY	VIGOR
1	Check	6.6	5.9	1.0	9.5
2	NaCl	6.5	5.3	7.5	4.3
3	$NaCl+Na_2SO_4$	7.1	5.5	6.5	4.2
4	$NaCl+Na_2SO_4+NaH_2PO_4$	11.9	8.6	3.1	7.3
5	$NaCl+Na_2SO_4+NaH_2PO_4+NaNO_3$	12.0	8.5	3.6	6.6
6	$NaCl+CaSO_4+CaHPO_4+Ca(NO_3)_2$	7.1	6.7	4.4	8.1
7	$NaCl+K_2SO_4+KH_2PO_4+KNO_3$	8.1	7.4	1.1	9.3
8	$NaCl+CaSO_4+K_2SO_4+CaHPO_4+KH_2PO_4$ $+KNO_3+Ca(NO_3)_2$	7.6	5.9	1.0	8.9

TABLE G-7

EFFECT OF COMPLEMENTARY ANIONS AND CATIONS IN THE ROOTING MEDIUM ON THE UPTAKE OF CHLORIDE, PHOSPHATE, SODIUM, CALCIUM AND POTASSIUM BY CORN SEEDLINGS

	YIELD (% OF DRY WEIGHT)				
TREATMENT	Cl	P	Na	Ca	K
Check	0.74	0.12	0.01	0.50	2.45
NaCl	2.24	0.12	0.03	0.50	2.03
$NaCl+NaSO_4$	2.20	0.12	0.02	0.51	1.73
$NaCl+Na_2SO_4+NaH_2PO_4$	1.01	0.21	0.03	0.31	0.76
$NaCl+Na_2SO_4+NaH_2PO_4+NaNO_3$	1.01	0.24	0.04	0.26	0.61
$NaCl+CaSO_4+CaHPO_4+NaNO_3$	1.55	0.26	0.02	0.46	1.03
$NaCl+K_2SO_4+KH_2NO_4+KNO_3$	1.24	0.18	0.01	0.48	2.80
$NaCl+CaSO_4+K_2SO_4+KNO_3+$ $Ca(NO_3)_2+CaHPO_4$	1.48	0.17	0.01	0.46	2.07

salts were more effective than calcium salts. There was an inverse relationship between the phosphate and chloride contents of tissues. As phosphate content increased in tissues, the chloride content tended to decrease. Also, potassium tended to reduce sodium absorption by corn. The results indicated that the use of potassium phosphate with deicing compounds may be effective in decreasing sodium and chloride uptake, thereby minimizing salt injury.

APPENDIX H

EFFECTS OF OSMOTIC PRESSURES OF NaCl AND $CaCl_2$ ON TRANSPIRATION AND PHOTOSYNTHESIS OF SOME DECIDUOUS TREES

Soluble salts provide the elements essential for plant growth, but excess amounts can be injurious. The most common plant response to excessive amounts of salt is a general reduction of growth; however, plants differ greatly in their tolerance to large amounts of salts. At a given rate of NaCl some plants show a stimulation of growth while other species may die (*23*).

The physiological basis for the pronounced differences to salt tolerance in different plant species is not known. Very little is known about the effects of salt on plant metabolism

(2). Two possible effects on plants of excessive available salts are a decrease in the rate of photosynthesis per unit leaf area and decreased utilization of photosynthates. Kling (24) reported an increase in the rate of photosynthesis per unit leaf area for salt-affected alfalfa and tomato plants. Hayward and Bernstein (23), working with barley, found that excessive salt affected utilization of photosynthates rather than the rate of photosynthesis. They also observed a lower rate of respiration in plants exposed to excessive amounts of salt.

RESEARCH APPROACH

The present study examined the effects of deicing salts NaCl and $CaCl_2$ on growth, rate of transpiration, and rate of photosynthesis. Three woody species of plants were used. These included sugar maple (*Acer saccharum*), redbud (*Cercis canadensis*), and honey locust (*Gleditsia triacanthos*). These three plant species were selected on the basis of their tolerance to or susceptibility to salt reported in earlier studies (25), sugar maple being susceptible to salt and redbud and honey locust being fairly tolerant of salt.

The plants were grown in gravel cultures in a greenhouse from June to December 1970. The experimental equipment consisted of 3-gal. size, glazed earthen crocks filled with fine gravel and provided with a drainage hole at one side. Each group of four crocks, representing four replications of the same treatment, had its own solution reservoir. At regular intervals, the salt solution was cycled through the gravel and back to the reservoir. The reservoir contained a total of 20 l of nutrient and/or salt solution. The composition of the nutrient solution, in millimoles per liter, was as follows: $Ca(NO_3)_2$—2.5; KNO_3—3.0; $MgSO_4$—1.5; KH_2PO_4—0.5. The solution also contained 1 ppm each of boron and manganese as H_3BO_3 and $MnSO_4$, respectively. Deionized water was used in preparing all solutions. The nutrient solution was considered as the zero salt level (control). The salt solutions, in addition to the above nutrient solution, consisted of enough of NaCl, $CaCl_2$, or KCl to increase the OP to ¼, ½, 1, and 2 atm (24-meq NaCl = 1-atm OP; 32-meq $CaCl_2$ = 1-atm OP; 24-meq KCl = 1-atm OP, respectively). The salt solutions were applied three months after the plants had become established in the gravel cultures. The volume of the salt solutions was maintained by adding deionized water and the pH was kept at about 6 by adding HNO_3.

Six-months-old plants were obtained and an excess number of plants were started, but later thinned to one healthy plant per crock. There were five cultures of each species, a control and four different levels of salt, each with four replications.

The weather was very warm during the first half of the growth period with mid-day temperatures in the greenhouse frequently at 100 F. This resulted in poor growth of plants with a number of them dying in the first three months.

Rate of transpiration was determined on two replications by determining weight loss due to water during a period of 225 hr. At the end of the study, the leaves were harvested and the weight of green leaves recorded.

During September, several typical leaves from each treatment were selected and photosynthesis of these attached leaves was measured (26). After recording photosynthesis, the leaf area was determined planimetrically.

TABLE H-1

EFFECT OF SALT TREATMENTS ON AVERAGE YIELD OF FRESH PLANT LEAVES

SPECIES	YIELD OF CONTROL (G/PLANT)	YIELD OF SALT-TREATED PLANTS AS PERCENTAGE OF CONTROL			
		¼ ATM	½ ATM	1 ATM	2 ATM
Sodium chloride					
Sugar maple	8.48	72.9	72.0	56.3	48.8
Redbud	13.10	108.2	116.7	121.7	115.8
Honey locust	10.16	116.9	129.6	146.9	149.8
Calcium chloride					
Sugar maple	8.99	78.7	69.6	66.9	46.7
Redbud	11.74	111.2	129.5	132.6	133.8
Honey locust	10.16	103.5	122.7	128.3	132.8
Potassium chloride					
Sugar maple	8.21	115.9	118.8	115.4	110.1
Redbud	10.75	115.1	124.5	132.6	143.0
Honey locust	8.74	111.5	117.4	120.4	116.2

TABLE H-2

EFFECT OF SODIUM CHLORIDE AND CALCIUM CHLORIDE ON RATE OF TRANSPIRATION

SALT	ATM	WATER TRANPIRED PER HOUR (ML)	MEAN WEIGHT OF LEAVES (G)	WATER TRANSPIRED BY LEAVES (ML/G)
Sugar maple				
Check:	0	3.7	8.47	0.43
NaCl:	¼	3.9	6.17	0.63
	½	3.9	6.11	0.64
	1	3.9	4.76	0.82
	2	3.9	4.14	0.94
$CaCl_2$:	¼	3.9	7.08	0.55
	½	3.9	6.26	0.62
	1	4.3	6.02	0.71
	2	4.3	4.19	1.00
Redbud				
Check:	0	4.2	13.09	0.32
NaCl:	¼	4.3	14.18	0.30
	½	4.4	15.30	0.28
	1	4.4	15.93	0.28
	2	4.4	15.67	0.28
$CaCl_2$:	¼	4.3	13.06	0.33
	½	4.3	15.20	0.28
	1	4.4	15.56	0.28
	2	4.3	15.72	0.28

RESULTS AND DISCUSSION

The average fresh yield of leaves including petioles of two replications was used to compare growth of control and salt-treated plants (Table H-1). The yields of salt-treated plants are reported as a percentage of the control.

The leaf yield data for redbud and honey locust indicate some stimulation of growth with salt treatments. Even 2 atm of NaCl, $CaCl_2$, or KCl, having the highest osmotic pressure of the salt solutions used, did not suppress the growth of these species. On the other hand, growth of sugar maple was suppressed by as little as ¼ atm of both NaCl and $CaCl_2$; KCl, however, had no deleterious effect even on sugar maple.

The amount of water transpired per gram of fresh leaves per hour was used to compare the effect of osmotic pressure of salt solutions on the tree species (Table H-2). Honey locust, during the period, was shedding leaves and was not used for the study.

There was no difference in the total amount of water transpired per hour by the two plant species due to differences in osmotic pressure of NaCl and $CaCl_2$ solutions compared with the control. However, there was a distinct (probably intrinsic) difference between the behavior of two plant species when comparing milliliters of water transpired per gram of leaves per hour. The amount of water transpired per gram of leaf per hour tended to increase in sugar maple with increases in osmotic pressure with NaCl and $CaCl_2$ and exceeded that of the control. On the other hand the tendency with respect to redbud was for a decrease in the amount of water transpired per gram of leaves per hour. The growth of sugar maple was suppressed by an increase in osmotic pressure. The increase in amount of water transpired per gram of leaves might be attributed either to the suppression of growth or the physiological behavior of sugar maple to adjust to osmotic pressure changes in the culture media by changing the osmotic pressure of the plant sap. An increase in osmotic pressure in the culture media is considered by some workers (*23*) to produce a moisture stress caused by the osmotic pressure of NaCl and $CaCl_2$ solutions. Bernstein and coworkers (*2*) indicated that the osmotic pressure of the leaves was maintained at relatively constant value approximately ten times higher than the osmotic pressure of the roots in cotton and pepper.

The slight decreases in the amount of water transpired per gram of leaves per hour by redbud may be attributed to the stimulation of growth due to salt solutions rather than a moisture stress.

The net carbon exchange data for leaves expressed on an area basis were used to measure the rate of photosynthesis (Table H-3).

TABLE H-3

EFFECT OF OSMOTIC PRESSURE OF SALT SOLUTIONS ON RATE OF PHOTOSYNTHESIS

		($MG\ CO_2/DM^2/HR$)				
SPECIES	SALT	0 ATM	¼ ATM	½ ATM	1 ATM	2 ATM
Sugar maple:	NaCl	8.9	8.9	7.4	7.4	7.5
	$CaCl_2$	8.9	8.4	10.9	6.7	7.4
Redbud:	NaCl	17.2	15.7	12.1	13.0	16.4
	$CaCl_2$	17.2	19.3	18.3	16.7	13.5

The rate of photosynthesis was suppressed with an increase in OP of both NaCl and $CaCl_2$ with respect to sugar maple. Even for the tolerant species (redbud), the rate of photosynthesis per unit leaf area tended to decline with the highest osmotic pressures. However, there was an apparent stimulation at ¼- and ½-atm OP of $CaCl_2$. It may be reasonable on the basis of results reported in Table H-3 to assume that there is a general tendency for suppression of photosynthesis in sugar maple with increasing osmotic pressures while this tendency was not so evident with redbud.

APPENDIX I

EFFECTS OF SODIUM CHLORIDE ON NITRATE ION ABSORPTION BY BARLEY SEEDLINGS

Increased wintertime use of NaCl (rock salt) and $CaCl_2$ for deicing of highways has been suspected to damage roadside vegetation. The direct causes of such plant injury are not known, but osmotic effects and sodium and chloride poisoning have been strongly implicated (see Appendix B).

Other possible sources of plant injury are nutritional imbalances or deficiencies indirectly produced by sodium, calcium, and/or chloride ions. These ions, which are the primary constituents of deicing salts used on highways, may compete for absorption sites on plant roots with elements essential for plant growth such as potassium (K), magnesium (Mg), nitrate (NO_3), or phosphate (H_2PO_4) ions and thereby limit the uptake of the essential elements.

This investigation sought to evaluate the possible competition of chloride versus nitrate ion absorption by intact 10-day-old barley seedlings.

REVIEW OF LITERATURE

Essential to a study of competition between chloride and nitrate ions is some knowledge of (a) ion absorption phenomena in general and, more specifically, (b) nitrate ion absorption.

Ion Absorption

For decades the study of ion absorption or uptake has been a prime endeavor of plant physiologists. Even so, the mechanisms by which ions move through cell membranes remain a mystery.

The Carrier Hypothesis

One of several hypotheses of the mechanism of ion absorption is the "carrier" hypothesis, which assumes the existence of a carrier molecule within a plant root membrane. The carrier molecule may attach itself to an ion at the membrane's outer surface and transport it to the inner surface. From there the ion can be transported elsewhere in the plant's root system or to the tops of the plant.

The carrier hypothesis can be explained and substantiated to a degree by applying Michaelis-Menten enzyme kinetic theory to data on ion absorption rates as Epstein and Hagen did in 1952 (*27*).

Ion competition, as may exist between chloride and nitrate ions, can also be illustrated using enzyme kinetics. These kinetic techniques are further explained later under "Discussion" and by Epstein and Hager (*27*) and Bosshard (*28*).

Dual Mechanisms of Ion Absorption

In conjunction with the carrier hypothesis, Epstein et al. (*29*) showed that plant roots absorb certain ions at two different rates: a slow absorption rate (mechanism 1) at low concentration (less than 0.5 mM) of ions in the root medium and a fast rate (mechanism 2) at high concentrations (greater than 1.0 mM). Low-concentration mechanism 1 is hypothesized to involve one kind of carrier that may actively transport ions at all ion concentrations. High-concentration mechanism 2 includes ions absorbed by the mechanism 1 carrier as well as ions absorbed by a second carrier, which operates only at external ion concentrations greater than 0.5 mM. Each of these carriers responds to competing ions uniquely. Although one mechanism may be affected one way (e.g., an increased, decreased, or unchanged ion absorption rate), the other mechanism may be affected quite differently. Concentrations of absorbed ions and competing ions strongly affect the activity of each mechanism.

Nitrate Ion Absorption

No report of studies on dual mechanisms of nitrate absorption appears to exist. Most attention has been directed toward other ions that do not undergo significant metabolic reactions, such as oxidation-reduction or incorporation into reactive modules, following the absorption process.

Nitrate is metabolized after absorption. This fact, coupled with the difficulties involved in precise nitrate and total nitrogen determinations, as well as the absence of easily usable radioactive nitrogen isotopes, accounts for the lack of information about nitrate absorption.

Effects of NaCl on NO_3 Absorption

Epstein (*30*) found that nitrate ions did not compete for the same carrier as chloride ions in barley roots at high concentrations (mechanism 2) of both nitrate and chloride. Stenlid (*31*) similarly showed that chloride and nitrate absorption isotherms responded differently to different treatments.

Somewhat contradicting Epstein and Stenlid, Lundegardh (*32*) found that 10.0 mM of nitrate decreased chloride uptake except during the initial 15 min. Nitrate absorption was reduced at all concentrations of chloride.

Photosynthesis, respiration, carbohydrate content, oxygen and carbon dioxide concentrations, microorganism contamination, solution, pH, age of plant tissue, temperature, and other ions may all affect nitrate absorption to varying degrees (*33, 34, 35*). These numerous potentially interacting factors illustrate the apparent complexity of nitrate absorption phenomena. They have made the elucidation of the nature of absorption processes particularly difficult.

RESEARCH APPROACH

Barley seeds (*Hordeum vulgare* L., var James), germinated for 36 hr in deionized water, were planted with emerging radicles (1 to 4 mm long) downward in stainless steel screen wire, which had been glued under a 6-cm-diameter aperture in a 15 × 15 × 0.6-cm piece of black plexiglass. This was placed on top of a 1-l aluminum-foil-covered beaker containing 0.5-mM solution of calcium sulfate ($CaSO_4$). The seeds were covered with aluminum foil and the solution aerated continuously. All plants derived from a unit as described constituted one culture.

Three days after planting on the screen, the aluminum foil was removed to expose the 1.5- to 2.0-cm-tall seedlings to 14 hr of light (about 2,500 ft-c) per day. Seedlings less than 1 cm tall were culled. A Sherer-Gillette walk-in growth chamber, which permitted light and temperature (21 to 22 C) control, was used for all phases of the experiments. Cultures were rotated daily to provide uniform light exposure.

Table I-1 presents the schedule for changing the root medium solutions. Concentrations of salts used in nutrient solutions are given in Table I-2. The pH of the undiluted stock solution was adjusted to 5.5 with potassium hydroxide (KOH). Nitrate ions were used as the nitrogen (N) source to assure induction of nitrate reductase (*37, 38*).

Two cultures were grown for each experiment. Because

TABLE I-1

SCHEDULE FOR CHANGING OF ROOT MEDIUM SOLUTIONS FOR BARLEY SEEDLINGS

DAYS AFTER PLANTING	SOLUTION
0	0.5mM $CaSO_4$
1	0.5mM $CaSO_4$
2	0.5mM $CaSO_4$
3	0.5mM $CaSO_4$
4	Complete nutrient
5	0.5mM $CaSO_4$
6	Complete nutrient
7	0.5mM $CaSO_4$
8	Complete nutrient
9	0.5mM $CaSO_4$
10	Experimental

TABLE I-2

CONCENTRATIONS OF SALTS IN COMPLETE NUTRIENT SOLUTIONS FOR BARLEY SEEDLINGS

SALT	MM/L	μ M/L
Ca (H_2PO_4)	0.5	—
$MgSO_4$	1.0	—
KNO_3	1.0	—
H_3BO_3	0.018	—
Fe-EDTA [a]	—	3.2
$MnCl_4$	—	3.2
$ZnSO_4$	—	0.29
$CuSO_4$	—	0.12
H_2MoO_4	—	0.042

[a] Iron sequestered in ethylenediaminetetraacetic acid (*36*).

six experiments were usually planned for one day, 12 cultures were grown simultaneously. On the tenth day each culture was exposed for 15 or 20 min to a holding solution, which was identical in concentration to the experimental solution. The holding solution provided nitrate ions necessary to fill the free space of the root tissue (*39*). After exposure to the holding solution, one of the two cultures for each experiment was harvested as a control and one was transferred to 1 l of the experimental solution. The root:solution ratios were nearly the same for all experimental cultures, (1 to 2 g dry weight per litre) and thus were below the critical fresh-weight-per-litre ration specified by Jacobson, et al. (*40*) for sodium and lithium absorption.

Harvesting involved rinsing the roots in deionized water for 5 min, blotting them with cheesecloth, and cutting them from the tops just below the screen. Both roots and tops were placed immediately in a 75 C oven for 24 hr. After drying, the weights of the parts were determined. Immediately following the prescribed time period, the experimental culture was harvested by the same procedure as for the control.

Experimental solutions were prepared by a method similar to that for nutrient solutions, except that the nitrate concentrations were varied. When the potassium nitrate (KNO_3) concentration was less than 1.0 mM, potassium sulfate (K_2SO_4) was used proportionally to maintain the potassium concentration at 1.0 mM. NaCl was added to experimental solutions as required. The pH's of the experimental nutrient solutions were between 6.2 and 6.4. Usually, during experimental periods pH fluctuations were within this range. Lycklama (*34*) found pH 6.2 optimal for nitrate absorption with perennial ryegrass (*Lolium perenne* L.)

The total time required for each experiment ranged from 30 min for the most dilute nitrate solutions (0.02 mM) to 6 hr for the most concentrated (7.0 mM). After specific time intervals, which ranged from 5 min (0.02 mM) to 1 hr (7.0 mM), the 1-l volume of experimental solution was renewed. The time intervals allowed for a measurable nitrate removal and minimal evapotranspiration losses, which were limited to 10 ml for the longest interval. Nitrate removal was usually about 25 percent of the original concentration and exceeded 50 percent only a few times at the lowest nitrate concentration. The solution removed at the end of an interval was sampled for nitrate determination by the steam distillation method (*41*). This method involves increasing the solution pH to approximately 9, distilling off the NH_4, and then reducing the nitrate with Devarda's alloy to NH_4, which is distilled as NH_3 into a boric-acid-indicator solution. This is titrated with standard acid.

Plant material was ground with a Wiley mill using a 40-mesh sieve. Samples of ½ g were weighed into 125-ml Erlenmeyer flasks, into each of which 100 ml of deionized water was added for extraction of nitrate and chloride ions. Samples were shaken for 45 min and filtered with Whatman No. 31 paper. The filtrate was analyzed for nitrate content by steam distillation (*41*) and for chloride by titration.

RESULTS

Table I-3 gives the actual nitrate and chloride concentrations in the nutrient solutions of each experiment.

The dependencies of the rates of nitrate absorption on concentrations are shown in Figures I-1, I-2, and I-3 for the three levels of NaCl, respectively. Note that these are simple plots.

When the reciprocals of the values (Figs. I-1, I-2, and I-3) are plotted as in Figures I-4, I-5, and I-6, combinations of straight lines may be more helpful in elucidating dual mechanisms. Justification for the methods used (Figs. I-4, I-5, and I-6) was presented by Robertson (*33*), who separated the two absorption mechanisms at approximately 0.5 mM—those concentrations less than 0.5 mM affect mechanism 1 and those greater than 0.5 mM affect mechanism 2. Two linear regressions were computed: one for values obtained from experiments done at concentrations less than 0.5 mM, and another for values from concentrations greater than 0.5 mM. The two equations on each of Figures I-4, I-5, and I-6 describe these double reciprocal plots.

Single linear equations were computed for each set of data in Figures I-4, I-5, and I-6 (see Table I-4). Deviation from linear regression analyses for both the single and dual linear equations showed that neither graphing method fitted

TABLE I-3

KEY TO ACTUAL NITRATE AND CHLORIDE CONCENTRATIONS IN NUTRIENT SOLUTIONS FOR EACH EXPERIMENT WITH 10 DAY-OLD BARLEY SEEDLINGS

EXP. NO.	SALT	CONCENTRATION (MM) LOW	MEDIUM	HIGH
2	NO_3	0.0116	0.0156	0.0112
	Cl	0.0034	0.1044	5.4055
2A	NO_3	0.0152	0.0121	0.0158
	Cl	0.0156	—	5.0793
4	NO_3	0.0315	0.0341	0.0332
	Cl	0.0008	0.1044	5.2884
6	NO_3	0.0450	0.0575	0.0590
	Cl	0.0008	0.1082	4.9997
6B	NO_3	0.0500	0.0500	0.0520
	Cl	0.0008	0.0974	4.9651
1	NO_3	0.0995	0.0995	0.0870
	Cl	0.0017	0.1035	4.9392
1A	NO_3	0.0855	0.0892	0.0887
	Cl	0.0033	0.0982	5.0066
20	NO_3	0.1920	0.1930	0.1900
	Cl	0.0123	0.1011	5.0101
20A	NO_3	0.2010	0.2005	0.2020
	Cl	0.0065	0.0834	5.0066
50	NO_3	0.4822	0.4790	0.4790
	Cl	0.0033	0.0854	4.9619
50A	NO_3	0.4805	0.5025	0.4800
	Cl	0.0016	0.0995	4.7921
10	NO_3	0.9670	0.9755	0.9750
	Cl	0.0041	0.0876	5.0239
10A	NO_3	0.9825	0.9955	0.9770
	Cl	0.0042	0.0938	5.0412
22	NO_3	1.9745	1.9665	1.9660
	Cl	0.0068	0.0946	4.9734
22A	NO_3	1.9615	1.9860	1.9610
	Cl	0.0076	0.0929	4.9862
44	NO_3	3.9170	3.9460	3.9060
	Cl	0.0000	0.0938	4.9519
77	NO_3	6.8810	6.8940	6.9020
	Cl	0.0034	0.0929	4.9734
77A	NO_3	6.8800	6.9600	6.9920
	Cl	0.0042	0.0971	4.9622

the points better than the other. Quadratic equations did not give a better fit to the points except in Figure I-6 (Fig. I-4, $r^2 = 0.68$; Fig. I-5, $r^2 = 0.76$; Fig. I-6, $r^2 = 0.97$).

Figures I-7 and I-8 show interactions among K_m and V_{max} values of Table I-5 for the high (0.5 to 1.0 mM) and low (0.0 to 0.5 mM) concentration ranges. K_m is the Michaelis constant, which is defined as that ion concentration producing one-half the maximum rate of absorption (V_{max}). The significance of the data in Table I-5 and Figures I-7 and I-8 is explained under "Discussion."

Graphing of the nitrate-absorption data of Figures I-1, I-2, and I-3 on a variable concentration scale (scale change at 0.2 mM) further upholds the dual mechanism theory for nitrate absorption. Such was done for Figures I-9, I-10, and I-11 in the manner in which Epstein et al. (*29*) presented potassium-absorption data.

DISCUSSION

Two nitrate absorption mechanisms are apparent when the rates of nitrate absorption are plotted against nitrate concentration and especially when double reciprocal plots are used (Figs. I-4, I-5, and I-6). These nitrate mechanisms are similar to dual mechanisms of other ions (*29, 42*).

Michaelis' Theory

Observation of the dual mechanisms depends on use of the Michaelis-Menten enzyme kinetic theory. This theory is based on

$$(E + S)\underset{k_2}{\overset{k_1}{=}}(ES)\overset{k_3}{=}E + \text{products} \qquad \text{(I-1)}$$

in which E stands for the enzyme, S for the substrate, and ES for the enzyme-substrate complex, which is assumed to attain instantaneous equilibrium with the E and S because of the frequently low concentration of E.

When applied to ion absorption, E represents the carrier and S represents the ion concentration. The ion-carrier complex ES is believed to "traverse" the membrane, at the inner side of which the complex releases the ion inside the cell (*43*).

The enzyme-kinetic approach to ion uptake is only a

TABLE I-4

K_m, V_{max}, AND r^2 VALUES FOR SINGLE LINEAR EQUATIONS OF DOUBLE RECIPROCAL PLOTS OF $\frac{1}{v}$ [RECIPROCAL OF RATE OF NO_3 ABSORPTION BY BARLEY SEEDLINGS—μM NO_3 ABSORBED $(HR)^{-1}$ $(G\ ROOTS)^{-1}$] VERSUS $\frac{1}{(S)}$ [RECIPROCAL OF mM NO_3 IN COMPLETE NUTRIENT SOLUTION] AT THREE CHLORIDE CONCENTRATIONS

CHLORIDE CONCENTRATION	V_{max}	K_m	EQUATION OF LINE	r^2
Low: (0.0000-0.0157)	0.1098	0.0181	$1/v = 0.1646 \quad 1/(S) + 9.104$	0.67
Medium: (0.0834-0.1082)	0.1178	0.0254	$1/v = 0.2161 \quad 1/(S) + 8.49$	0.70
High: (4.7921-5.4055)	0.1185	0.0349	$1/v = 0.2947 \quad 1/(S) + 8.44$	0.69

model and a tool used to describe a complicated phenomenon. In view of the fact that ion uptake experiments are not performed with purified substances *in vitro* but with complex living tissues, variability may be expected. Even when applied to enzyme reactions, Michaelis' theory is frequently criticized for its oversimplification. Limitations are numerous. In spite of its shortcomings, it has been used extensively to describe enzyme reactions and ion transport.

Consequently, one cannot be sure of the absolute existence of high- and low-concentration mechanisms for nitrate despite the evidence so similar to that for other ions. Dixon and Webb (*44*) warned that assumptions made in the Michaelis treatment of data may give an equation that fits the experimental data, but this is not proof that the assumptions are correct. A number of other assumptions may lead to the same equation. Actually, all other possible reactions under varying conditions must be proven incorrect before application of simple Michaelis theory and use of conclusions therefrom are valid.

Several sources of evidence may cause one to question the existence of dual mechanisms for nitrate. Because the quadratic equations give approximately the same r^2 values as linear equations (Table I-4), the mechanism for all absorption values considered together may obey second-order kinetics. Also, because approximately 25 to 30 percent of the variation for each of the linear, quadratic, and separate linear equations (of mechanisms 1 and 2) is un-

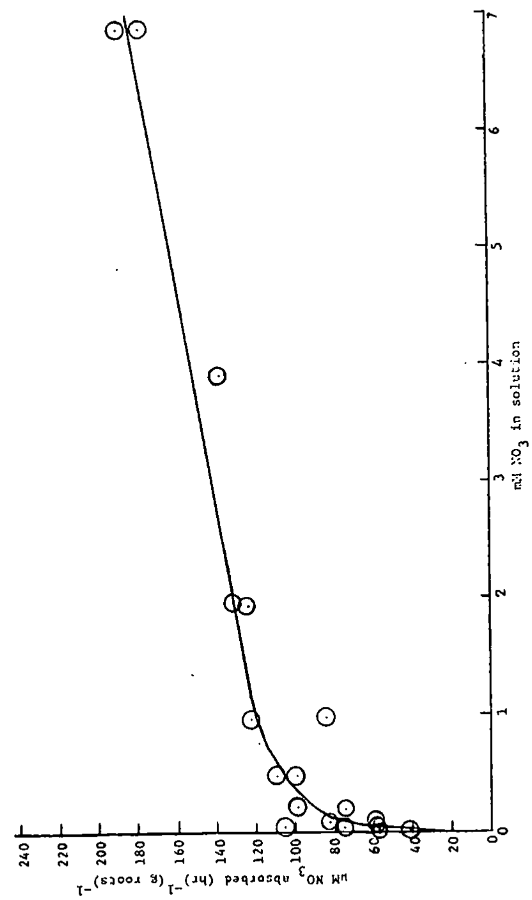

Figure I-1. Langmuir adsorption isotherm (22 C) for the rate of nitrate absorption by 10-day-old barley seedlings versus nitrate concentration of nutrient solutions with low sodium chloride (0.0000 to 0.0157 mM).

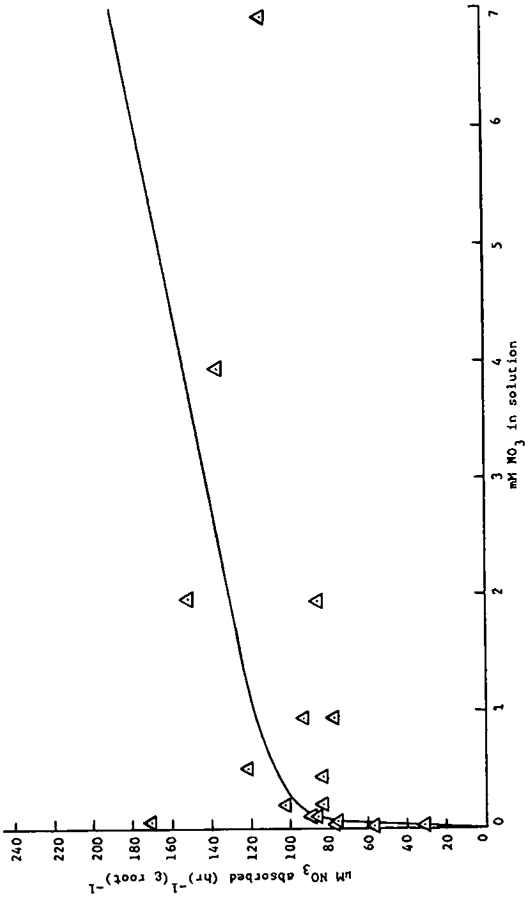

Figure I-2. Langmuir adsorption isotherm (22 C) for the rate of nitrate absorption by 10-day-old barley seedlings versus nitrate concentration of complete nutrient solutions with medium sodium chloride (0.0834 to 0.1082 mM).

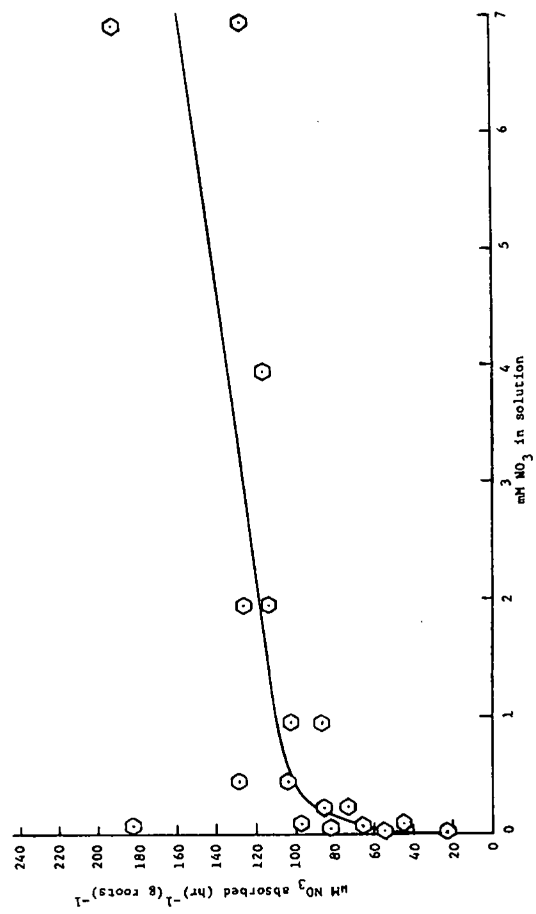

Figure I-3. Langmuir adsorption isotherm (22 C) for the rate of nitrate absorption by 10-day-old barley seedlings versus nitrate concentration of nutrient solutions with high sodium chloride (4.7921 to 5.4055 mM).

accounted for, third-order (or higher) kinetics may be the model describing the absorption process. Interpretation of higher-order kinetics is so complex that it is frequently avoided. However, the reduction, translocation, and assimilatory processes may exert such unique effects on nitrate absorption that third-order kinetics is worth consideration.

Langmuir Isotherms

A Langmuir (*45*) adsorption isotherm can describe the relationship between the rate of metabolically dependent ion absorption and the concentration of ions in solution (*34*). The Langmuir adsorption isotherms, shown in Figures I-1, I-2, and I-3, confirm Lycklama's (*34*) data with perennial ryegrass, in which he found 0.033 mM of potassium. These figures also illustrate the limitations of Langmuir adsorption isotherms as useful tools in ion absorption studies. Reexamination of Lycklama's data reveals that dual mechanisms may have been operating. The existence of these two mechanisms has been obscured because Lycklama did not (a) publish tables of absorption values and actual nitrate concentrations (such as occur in Table I-1), (b) present reciprocal plots, and (c) use nitrate concentrations in excess of 10 mM.

K_m and V_{max} Values

The data in Table I-4 for V_{max} and K_m are similar to the limited information on which Lycklama (*34*) based his discussion of a single mechanism. If Lycklama had been looking for dual mechanisms, he might have detected two

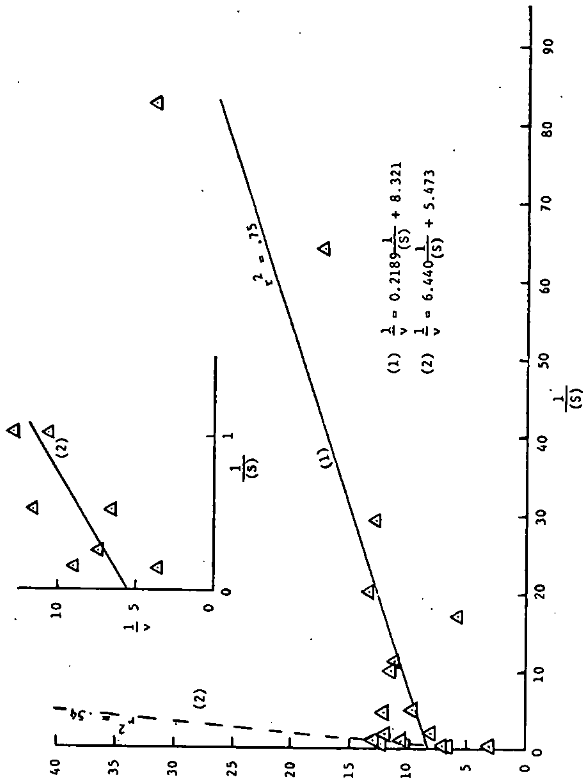

Figure I-5. Double reciprocal plot illustrating mechanisms 1 and 2 of nitrate absorption by 10-day-old barley seedlings for medium sodium chloride (0.0834 to 0.1082 mM).

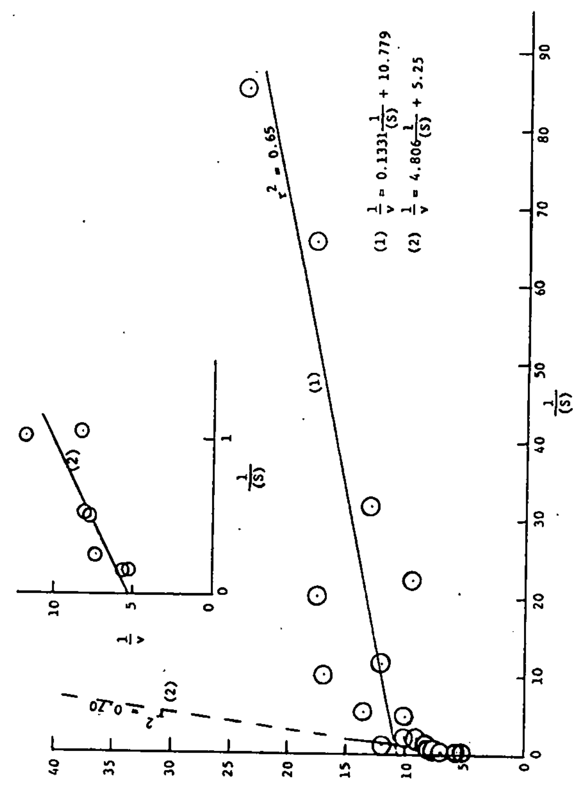

Figure I-4. Double reciprocal plot illustrating mechanisms 1 and 2 of nitrate absorption by 10-day-old barley seedlings for low sodium chloride (0.0000 to 0.0157 mM).

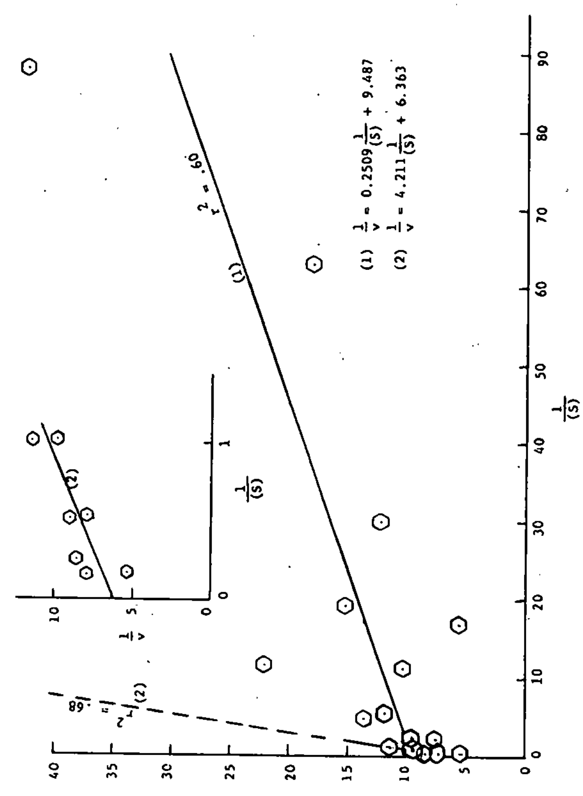

Figure I-6. Double reciprocal plot illustrating mechanisms 1 and 2 of nitrate absorption by 10-day-old barley seedlings for high sodium chloride (4.7921 to 5.4055 mM).

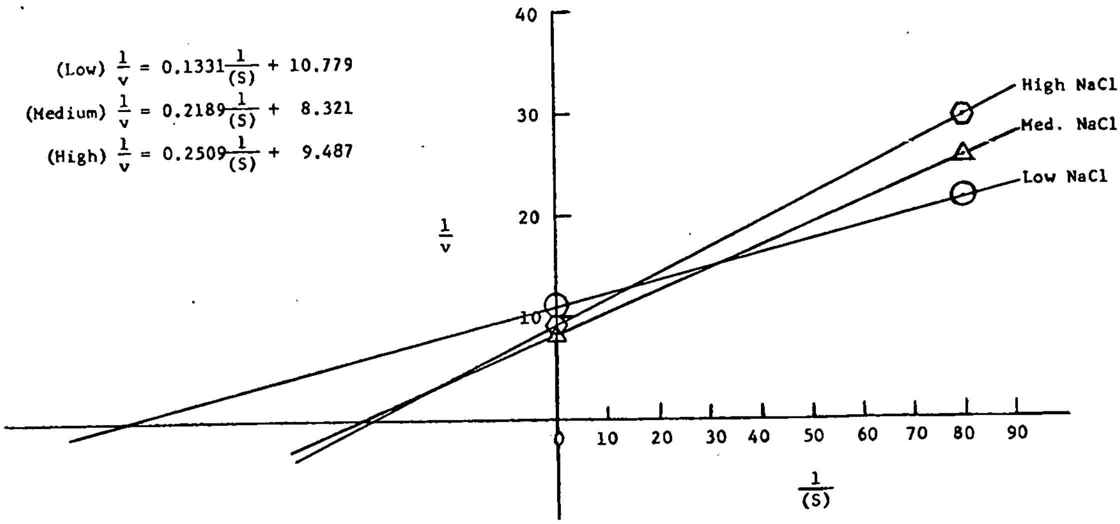

Figure I-7. Double reciprocal plot of equations for mechanism 1 of nitrate absorption at three concentrations of sodium chloride (low: 0.0000 to 0.0157. mM; medium: 0.0834 to 0.1082 mM; high: 4.7921 to 5.4055 mM).

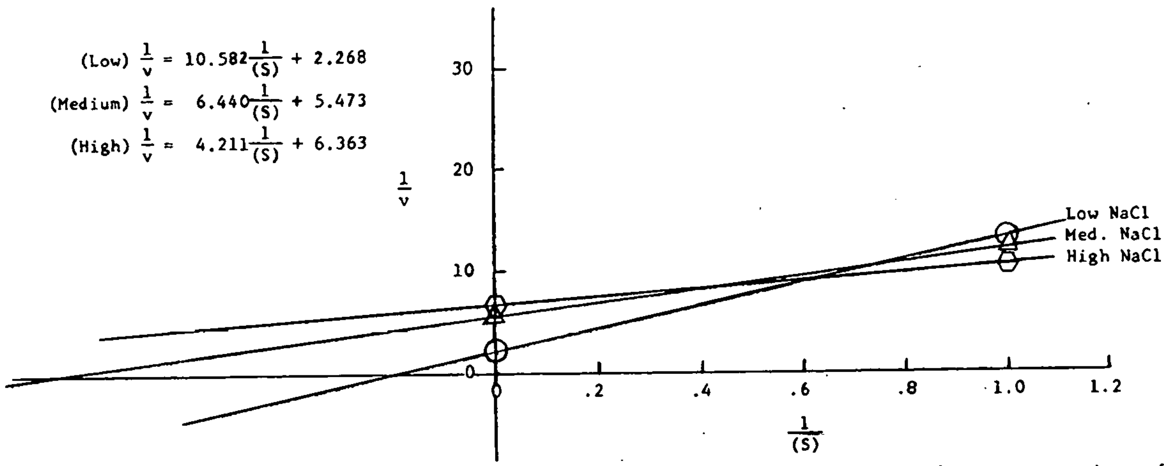

Figure I-8. Double reciprocal plot of equations for mechanism 2 of nitrate absorption at three concentrations of sodium chloride (low: 0.0000 to 0.0157 mM; medium: 0.0834 to 0.1082 mM; high: 4.7921 to 5.4055 mM).

TABLE I-5

K_m, V_{max} AND r^2 VALUES FOR THE MECHANISM 1 AND MECHANISM 2 LINEAR EQUATIONS (SEE FIGS. I-4, I-5, AND I-6) OF DOUBLE RECIPROCAL PLOTS OF $\frac{1}{v}$ VERSUS $\frac{1}{(S)}$ AT THREE CHLORIDE CONCENTRATIONS

CHLORIDE CONCENTRATION	MECHANISM 1				MECHANISM 2			
	V_{max}	K_m	EQUATION OF LINE	r^2	V_{max}	K_m	EQUATION OF LINE	r^2
Low: (0.0000–0.0157)	0.09277	0.0124	$1/v=0.1331\ 1/(S)+10.779$	0.65	0.4409	4.666	$1/v=4.806\ 1/(S)+5.25$	0.70
Medium: (0.0834–0.1082)	0.12018	0.0263	$1/v=0.2189\ 1/(S)+8.321$	0.75	0.18272	1.177	$1/v=6.440\ 1/(S)+5.473$	0.54
High: (4.7921–5.4055)	0.1054	0.0264	$1/v+0.2509\ 1/(S)+9.487$	0.60	0.15716	0.66196	$1/v=4.211\ 1/(S)+6.363$	0.68

V_{max} values from a Langmuir curve. But two different K_m values were obscured without reciprocal plots.

K_m and V_{max} values in Table I-4 show similar trends as exist for mechanism 1 (low nitrate concentration range) in Table I-5, suggesting that the over-all effect of NaCl may have altered the binding of nitrate to its carrier(s). Because little change occurred among V_{max} values (Table I-4), the perhaps erroneous conclusion—that NaCl had a negligible effect on the breakdown of the ion-carrier complex (of a single absorption mechanism)—might be drawn.

Reciprocal plots delineated the two mechanisms described in Table I-5, where K_m (4.66 mM) for high-concentration mechanism 2 is much larger than that for mechanism 1 (0.0124 mM). The high K_m for mechanism 2 indicates that the carrier presumed to be operating in this concentration range has a low affinity for nitrate ions. The low K_m for mechanism 1 suggests that its carrier has a high affinity for nitrate. This agrees with previous work (*42*) regarding the primary properties of both mechanisms. Note also in Table I-5 that V_{max} for mechanism 2 is greater than that for mechanism 1; this contrast is also in agreement with dual mechanisms for other ions (*33*).

Ion Inhibition

The kinetic analysis of enzyme reactions has been extended to include the effects of inhibiting substances. With respect to ion absorption kinetics, such inhibitors would include ions other than that for which absorption rate is being

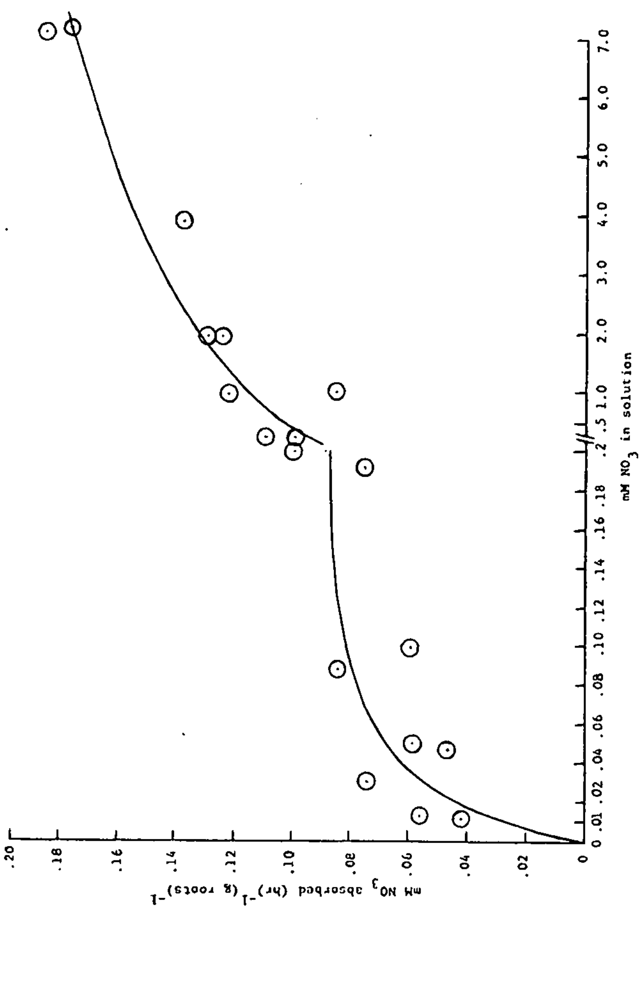

Figure I-9. Rate of nitrate absorption by 10-day-old barley seedlings versus nitrate concentration in complete nutrient solutions with low chloride concentrations (0.0000 to 0.0157 mM), according to horizontal scale of Epstein et al. (29).

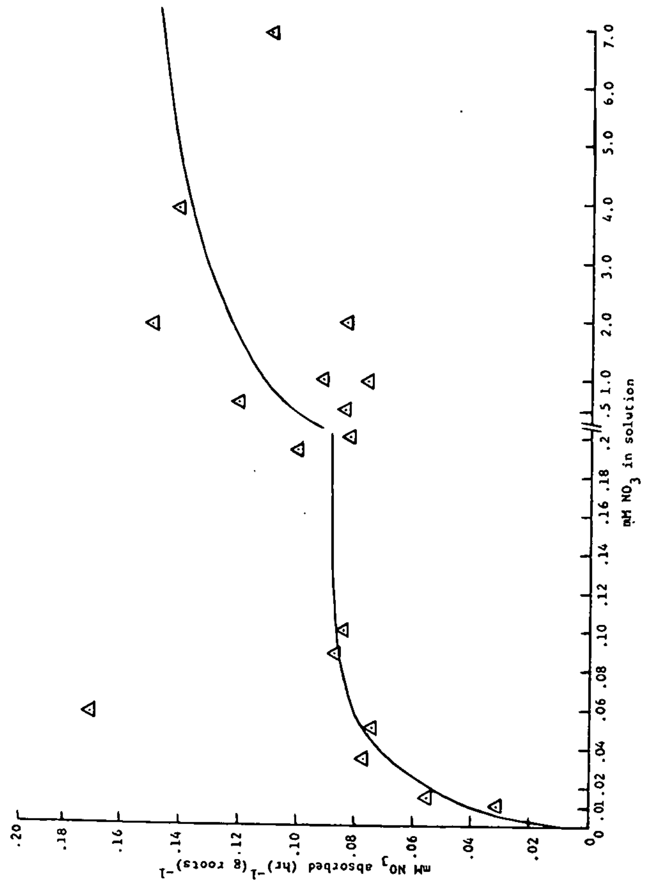

Figure I-10. Rate of nitrate absorption by 10-day-old barley seedlings versus nitrate concentrations in complete nutrient solutions with medium chloride concentrations (0.0834 to 0.1082 mM), according to horizontal scale of Epstein et al. (29).

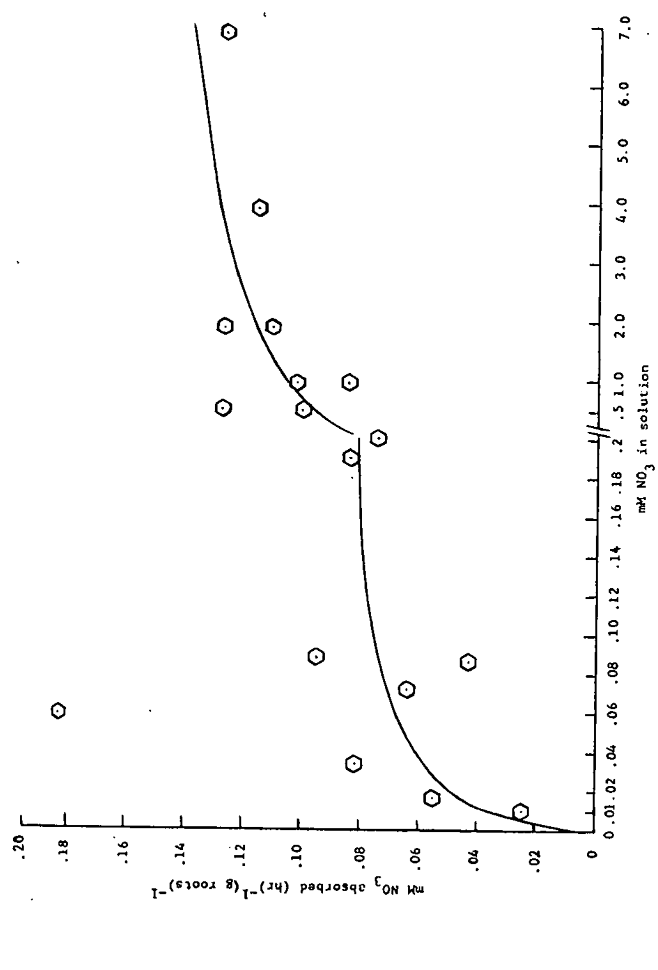

Figure I-11. Rate of nitrate absorption by 10-day-old barley seedlings versus nitrate concentration in complete nutrient solutions with high chloride concentration (4.7921 to 5.4055 mM), according to horizontal scale of Epstein et al. (29).

studied. Three common types of inhibitors occur: competitive, noncompetitive, and mixed. Although intended for application to enzyme reactions, these kinds of inhibition will be related to ion absorption (*27*).

Competitive Inhibition.—In competitive inhibition, the inhibitor (competing ion) combines with the carrier at the same site or reactive group as the substrate ion so as to compete with the substrate ion for available sites. Relative inhibition of the absorption of the substrate ion will depend on the concentrations of both the substrate ion and the competing ion. When the absorption values for the substrate ion in the presence of a competing ion are plotted by the Lineweaver and Burk (*46*) method (i.e., double reciprocal plots), the slope of the resulting line is greater than the slope of substrate ion absorption values obtained in the absence of a competing ion. The horizontal axis intercept also increases, but the vertical intercept does not change.

Noncompetitive Inhibition.—When the competing ion combines with the carrier irrespective of the presence of the substrate ion (i.e., it combines with both carrier and ion-carrier complex at a site different from the one to which the substrate ion attaches itself), the resulting condition is noncompetitive inhibition. The double reciprocal plot of this kind of inhibition gives a straight line for which both the slopes and vertical intercept are greater than those for the line computed for substrate ion absorption in the absence of competing ions. The horizontal intercept is not affected by this type of inhibition.

Mixed Inhibition.—If a competing ion affects both V_{max} and K_m, it causes a mixture of competitive and noncompetitive effects. Consequently, the slope and both axis intercepts are altered by the competing ion.

The following discussions of the effects of NaCl on mechanisms 1 and 2 are based on the foregoing model. One must remember that the complexity of the nitrate metabolism of intact seedlings growing in complete nutrient solutions precludes the absolute acceptance of these simplified explanations of ion competition.

Mechanism 1

Figure I-7 illustrates mechanism 1 at three concentrations of NaCl. The mixed type of inhibition best describes the relationships between nitrate absorption and NaCl. Chloride (medium and high concentrations) has altered the horizontal- and vertical-axis intercepts and the slope (K_m/V_{max}) of the low chloride concentration treatment. These alterations may be due to both competitive and noncompetitive inhibition.

However, note that the two lines for medium and high chloride concentrations have similar horizontal intercepts ($-1/K_m$). This means that the K_m's with chloride are essentially the same. The different slopes and vertical intercepts indicate that chloride exerts competitive inhibition on the mechanism 1 carrier, but that differences between the two chloride levels (medium and high) do not affect this inhibition. Once a small amount of chloride (approximately 0.1 mM or less) saturates the nitrate carrier, an increase in the amount of chloride will not alter this effect.

Inasmuch as the slopes increase and the horizontal intercept ($-1/K_m$) changes little with increasing chloride, chloride decreases the V_{max}, thereby retarding those reactions involved in the breakdown of the ion-carrier complex. This illustrates noncompetitive inhibition, which might not be significant if one considered only the vertical intercept ($1/V_{max}$) because medium and high chloride appear similar when calculating effects on V_{max}.

Mechanism 2

The mixed type of inhibition also appears in the high-concentration range (mechanism 2) (Fig. I-8). However, the response of mechanism 2 to NaCl is different from that of mechanism 1. The striking decreases in K_m values from 4.66 mM (low chloride) to 1.177 mM (medium chloride) and further to 0.662 mM (high chloride) suggest that NaCl increases the affinity of nitrate for the mechanism 2 carrier. This effect of NaCl on the mechanism 2 values of K_m is the reverse of the NaCl effects on mechanism 1 values of K_m.

The V_{max} values of mechanism 2 decrease with increasing NaCl. The NaCl itself, or some artifact caused by the elevated NaCl (e.g., ionic strength, effects of other ions, or pH differences), diminished the rate of dissociation of the ion-carrier complex either by direct action or by inhibition of nitrate translocation, reduction, and/or assimilation reactions.

pH Fluctuations

Examples of pH fluctuations during 4-hr experimental periods are given in Table I-6. As found by Ashley (*35*), the pH declined initially due to rapid cation absorption concurrent with nitrate absorption. Perhaps after the cationic demands of the plant were met, the pH increased as rapid nitrate uptake dominated ion absorption. The negative charge of nitrate was probably balanced either by exchange for bicarbonate (HCO_3) ions from organic acids or for

TABLE I-6

PH CHANGES OF COMPLETE NUTRIENT SOLUTIONS WITH VARYING NITRATE CONCENTRATIONS (ORION RESEARCH DIGITAL pH/MV METER, MODEL 801) AFTER EXPOSURE TO CULTURES OF 10-DAY-OLD BARLEY SEEDLINGS

APPROX. NITRATE CONC. (MM)	pH CHANGES 0	1	2	3	4	CULTURE DRY WEIGHT (G)
0.10	6.285	6.090	6.166	6.200	6.240	5.668
0.30	6.350	—	6.135	—	6.375	6.183
0.40	6.360	—	6.202	—	6.465	5.997
0.50	6.237	—	—	—	6.156	6.511
0.90	6.230	—	—	—	6.106	5.951
1.00[a]	6.250	—	—	—	6.400	6.566

[a] Includes approx. 5.0 mM NaCl.

hydroxide (OH) ions from nitrate reduction ($NO_3^- + 8H \longrightarrow NH_3 + 2H_2O + OH^-$) (*47*) or by concomitant hydrogen-ion uptake.

Nutritional and Interionic Effects

Because cultures were given a 0.5-mM $CaSO_4$ solution for 24 hr preceding the experimental period, the supply of utilizable carbohydrates, although not determined, was probably sufficient to provide carbon skeletons for amino acid synthesis and electrical neutralization of absorbed cations (*33*).

Provision of complete nutrient solutions during experiments and for 3 days during the 10-day growth period should have eliminated mineral deficiencies. However, interionic effects resulting from the increasing nitrate and NaCl concentrations are probably the most difficult to comprehend. Single-salt solution studies demonstrate that interionic competitions exist. What occurs when many salts are involved is an unanswered question.

In spite of the numerous environmental and physiological factors influencing nitrate absorption, dual mechanisms appear to exist, and NaCl, or only chloride, affects these mechanisms in specific ways. In general, NaCl decreases nitrate absorption, which confirms Epstein's (*30*) findings that nitrate competes with chloride. Epstein, however, used more concentrated (above 1.0 mM) solutions than those used in this study.

Additional research should give careful consideration to the variability of the plant material. Sizing of seeds and repeated selections for uniform seedlings might help, as well as improved aeration and growth chamber conditions. Future objectives should focus on interionic effects. If the nutrient solutions are analyzed as they were for nitrate in this research, fluxes of all major anions and cations should also be observed. When accompanied by pH changes and organic acid analyses of plant tissue, the total ionic activities of plants could be described.

To further resolve the dual mechanism of nitrate absorption, one might minimize the influences of reduction and assimilation reactions on absorption. Possible methods of inhibiting or diminishing nitrate reduction include the use of (a) para-chloromercuribenzoate (PCMB) to inhibit nitrate reductase, a sulfhydryl enzyme (*48*); (b) reduced oxygen tension to encourage competition for reductant between oxygen and nitrate (*49*); (c) levels of NH_4 sufficient to inhibit nitrate reduction (*34*); (d) no molybdenum in nutrient solutions (*34*); and (e) 35 C temperatures, at which nitrate reduction is presumed to be inhibited (*34*).

APPENDIX J

MOVEMENT OF DEICING SALTS IN SOILS

Surface applications of deicing salts move rapidly with infiltrating water under natural rainfall conditions to depths within the soil profile. Extremely high salt concentrations develop on the soil surface due to applications and, subsequently, to surface evaporation. Salt levels in the top soil drop far below those in the surface ½ in. There is usually an accumulation of salts in the upper subsoil and then a gradual reduction of the salt concentration with greater depth. As leaching continues, the pattern of salt movement tends to approach a more uniform salt concentration with depth through the soil profile.

The bulk of NaCl and $CaCl_2$ was leached from all three soils under natural rainfall conditions in a period of three years. The rates of movements varied with soils. However, specific conductance, chloride, and the cations of the salts (sodium, calcium) all gave similar patterns of salt movement. Chloride movements for the $CaCl_2$ treatments were slightly slower than for the NaCl treatments.

Applications of deicing salts affect the chemistry of the entire soil profile. Both NaCl and $CaCl_2$ suppressed soil pH, the latter salt more so than the former. The increased concentrations of the sodium and calcium in soil solution greatly increases the percentage of sodium and calcium on the exchange complex of the soil. Under natural leaching conditions the extent of sodium exchange for aluminum was not great enough in these acid soils to promote a great deal of dispersion.

MATERIALS AND METHODS

Field experiments described in Appendix C provided the basis for this part of the study. To measure the movements of chloride salts through the soil profile certain salt treatments were selected from these field experiments, which were established to study salt tolerance of plants. A split-plot design was used that allowed for twelve plots (18 × 27 ft) to be individually treated with salts. Plots from which soil samples were taken contained six deciduous tree species planted in random rows of nine plants on 3-ft centers.

Sodium chloride (NaCl—rock salt) and calcium chloride ($CaCl_2$), commonly used for highway ice removal, had been applied. The rates and time of application of chloride salt treatments are given in Table J-1. Treatments were applied in split applications during January, February, and early March. A granular form of the rock salt and a flake form of $CaCl_2$ were broadcast by hand on the surface of the soil. Soil samples were taken by genetic horizon to a depth of about 50 in. Surface soil samples represented a composite of 20 random cores and subsoil samples a composite of four subsamples, one from each quarter of the plot. All samples were air dried and ground to pass through a 2-mm-mesh sieve. Soils were equilibrated using a deionized water:soil ratio of 2:1. The pH of this suspension was measured and Cl, Na, Ca, and specific conductance of the filtrate were determined according to laboratory procedures.

TABLE J-1

DEICING SALT TREATMENTS

SALT TREATMENT	(LB/ACRE)	DATE OF APPLICATION [a]	
Check:	0		
NaCl:	1,500	1967–68	1968–69
	3,000	—	1968–69
	6,000	1967–68	—
$CaCl_2$:	1,500	1967–68	1968–69
	3,000	—	1968–69
	6,000	1967–68	—

[a] Six split applications applied during January, February, and on March 15.

RESULTS AND DISCUSSION

Application of both NaCl and $CaCl_2$ on a Sassafras soil suppressed the soil pH (Fig. J-1). The relative magnitude of suppression was greater for the $CaCl_2$ treatments, apparently due to a high exchange of calcium for aluminum (Al) and, subsequently, a greater degree of aluminum hydrolysis. Such decreases in pH occurred with depth in the soil to the water table. Similar results were found for the Groseclose soil (Fig. J-2) and Nason soil (Fig. J-3), but the data were more variable. The slight rise in pH in the Nason surface soil indicates that the salts had apparently been leached out, because chemically one would suspect the Nason soil to have a lower salt pH compared to the water pH.

It was found that as salt concentration in the soil increased, pH decreased. However, as the salt concentration in soil decreased from leaching by rainfall, the soil pH increased. In fact, the soil pH raised to a higher value after salt leaching than it was originally (Figs. J-4 and J-5). This indicates that some of the buffering compounds, probably aluminum groups, were removed with the salts.

To determine the movement and the distribution of the deicing salts with depths in the soils, both the specific conductance and the individual ions of the salt were measured. Specific conductance is an excellent indicator of the total soluble salt concentrations in soil solution. If the conductance is plotted on the same graph with the ions species, a relationship develops that shows not only the total salt concentration but also which ion of the salt is contributing to this concentration. These values are plotted for the Sassafras (Figs. J-6-J-10), Groseclose (Figs. J-11-J-15), and Nason soils (Figs. J-16-J-21).

The salt concentration of the treated soils was extremely high within the surface ½ in. This was attributed to the movements of soluble salts upward with soil water and subsequent concentration by evaporation. Much lower salt concentrations occurred below the ½-in. depth. Patterns of salt distribution in the soils showed an increase in the salt concentration at the beginning of the subsoil, which increased to a maximum and then gradually decreased with depth. At the depth of 40 to 50 in., the salt concentration approached the value of the untreated soil.

In general, specific conductance was a good indicator of the ion movements of both NaCl and $CaCl_2$. The higher the rates of salts applied, the greater the specific conductance, indicating greater salt concentrations. The amount of salts added greatly exceeded the exchange capacity of the soil, thus the salts moved freely in soil solutions. Chloride ion concentrations were slightly higher in the salt water extracts as compared to the cations (sodium and calcium) of the salts. The fact that chloride ions were slightly higher than cations indicates that cations other than those from the specific salts were present in soil solutions. This would have to occur to satisfy the negatively charged chloride ions.

The movement of deicing salts through the soil profile was rapid. Soil samples taken in June 1968 after applying 3,000 lb per acre of NaCl in split applications in January, February, and March of 1968 showed salt movements to the lowest depth samples (40 to 50 in.). The concentrations were, however, lowest for the deepest soil samplings.

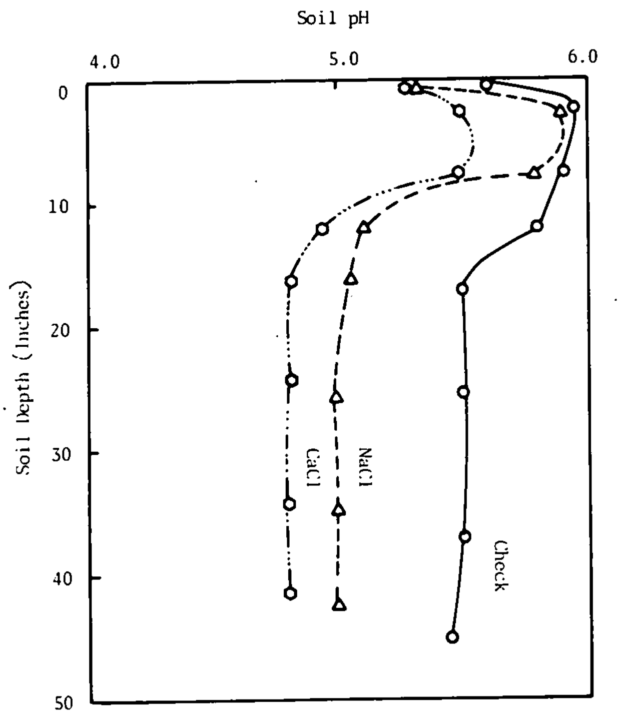

Figure J-1. Average effects of sodium chloride and calcium chloride on pH of Sassafras soil at various depths (Warsaw, Va., June 1968).

Very high concentrations of salt remained in the soil profile for all of the salt treatments sampled in June 1968. This was especially true for the 6,000-lb-per-acre rates, even though it was applied in one application in 1967. The soils without deicing salt applications had very low contents of soluble salts (Table J-2). The values for the different soils given in Table J-2 should be compared with the values of the same soils that had applications of the two deicing salts as given in the figures.

Calcium chloride moved slightly slower down through

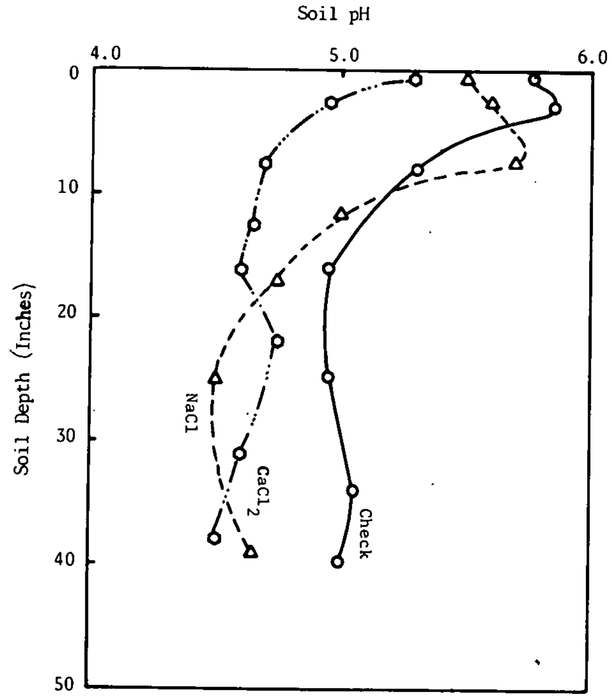

Figure J-2. Effects of sodium chloride and calcium chloride on pH of Groseclose soil at various depths (Blacksburg, Va., June 1968).

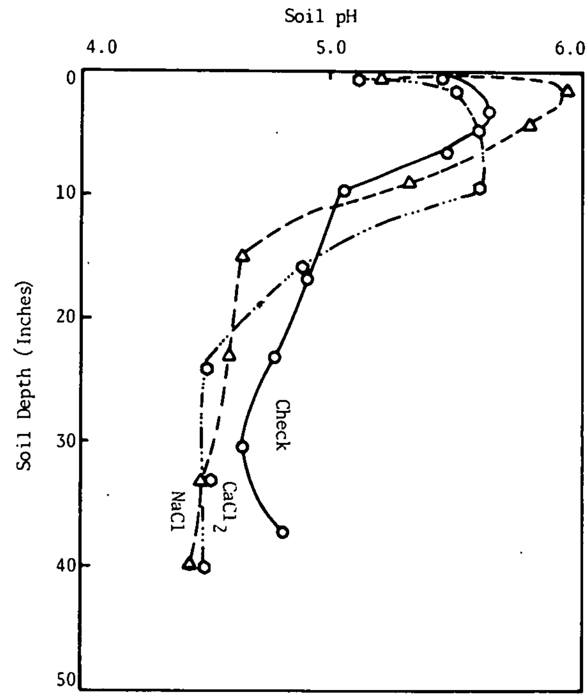

Figure J-3. Average effects of sodium chloride and calcium chloride on pH of Nason soil at various depths (Orange, Va., June 1968).

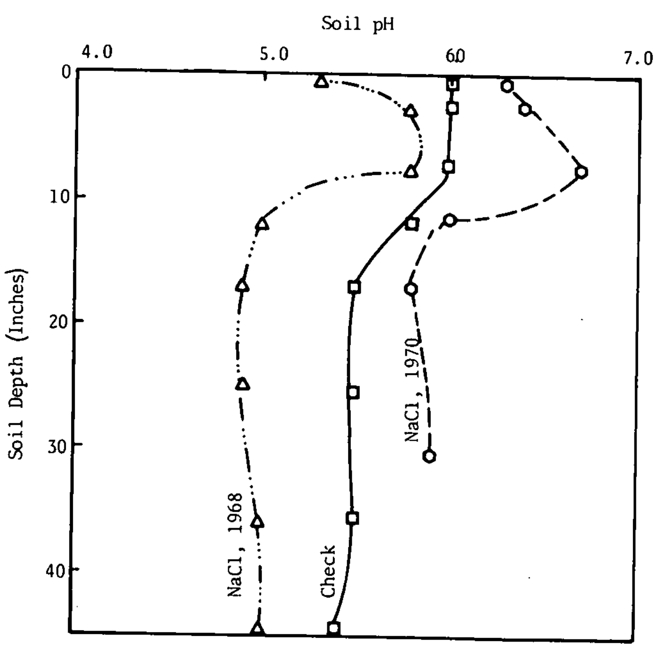

Figure J-4. Change in pH Sassafras soil at various depths with time as affected by sodium chloride treatment of 6,000 lb per acre (Warsaw, Va.).

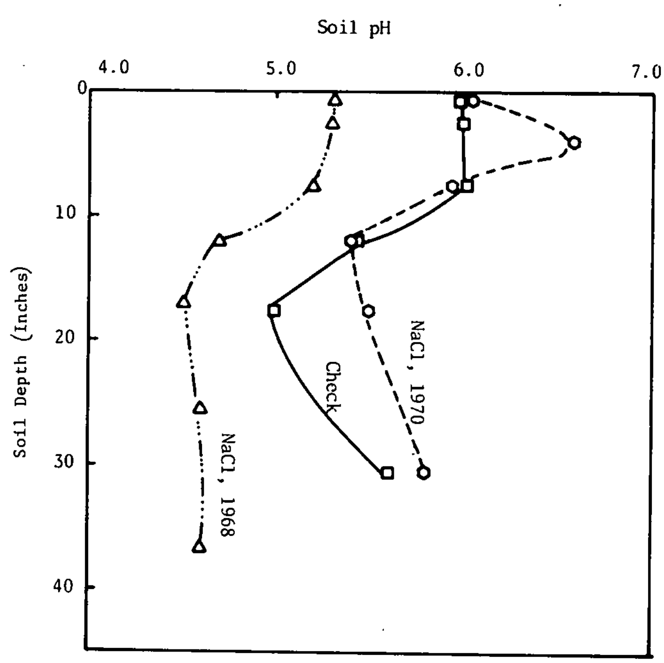

Figure J-5. Change in pH of Groseclose soil as affected by sodium chloride treatment of 6,000 lb per acre (Blacksburg, Va.)

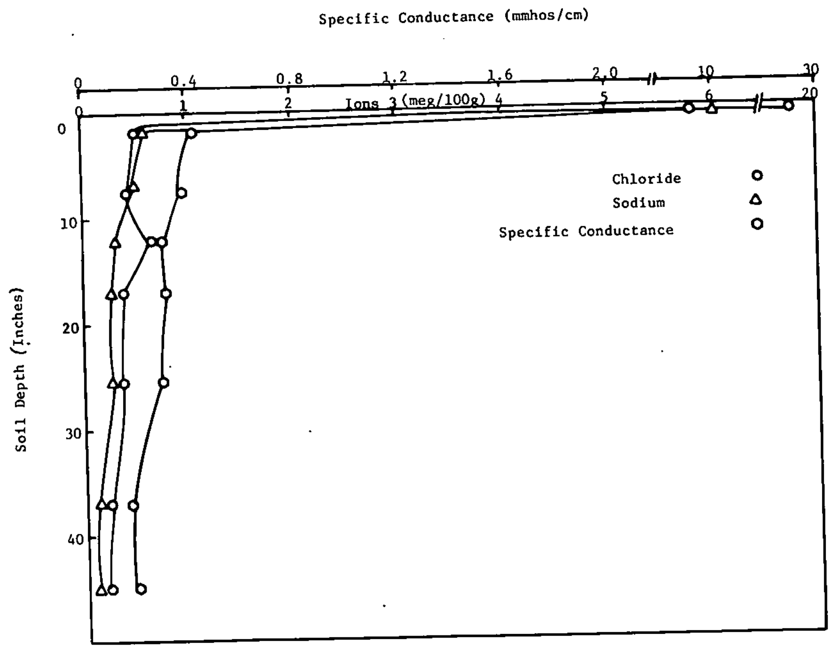

Figure J-6. Specific conductance as well as chloride and sodium concentrations in a Sassafrass soil in June 1968. Sodium chloride was applied on the surface the previous winter.

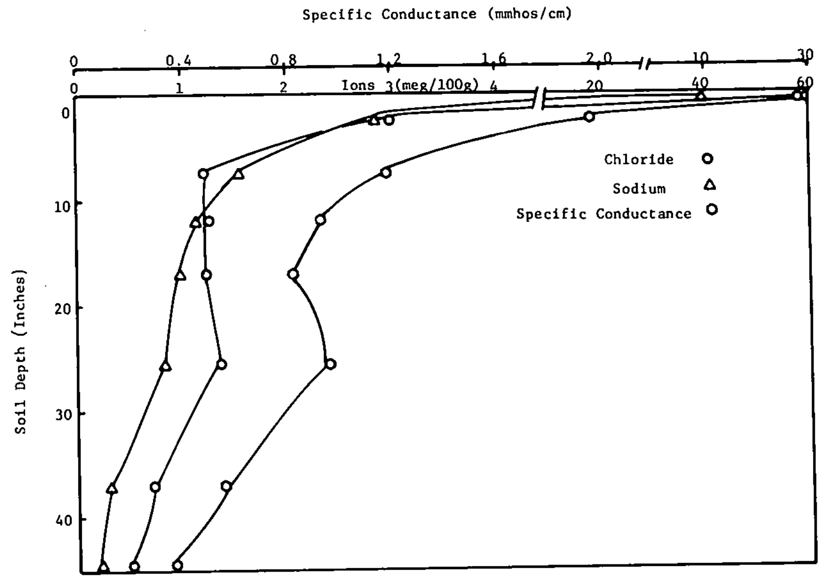

Figure J-7. Specific conductance as well as chloride and sodium concentrations in a Sassafrass soil treated with sodium chloride at 6,000 lb per acre (Warsaw, Va., June 1968).

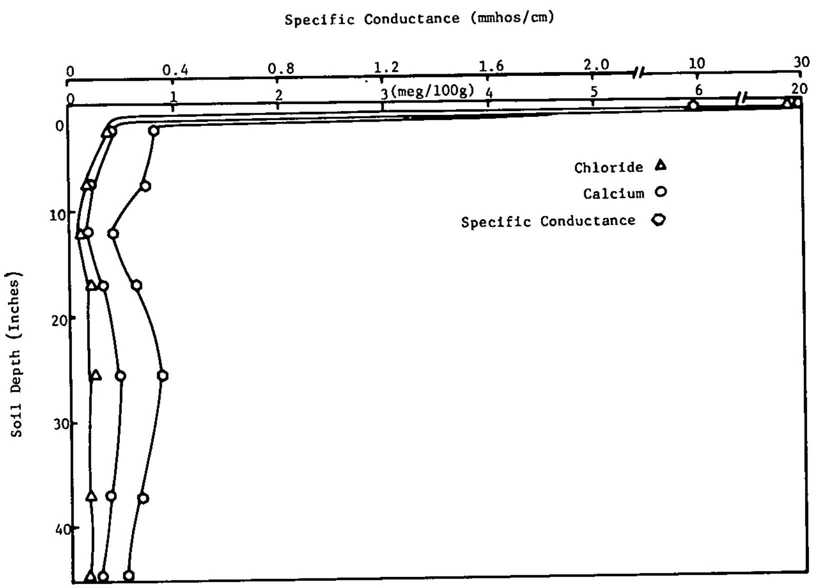

Figure J-8. Specific conductance as well as chloride and calcium concentrations in a Sassafrass soil treated with calcium chloride at 1,500 lb per acre (Warsaw, Va., June 1968).

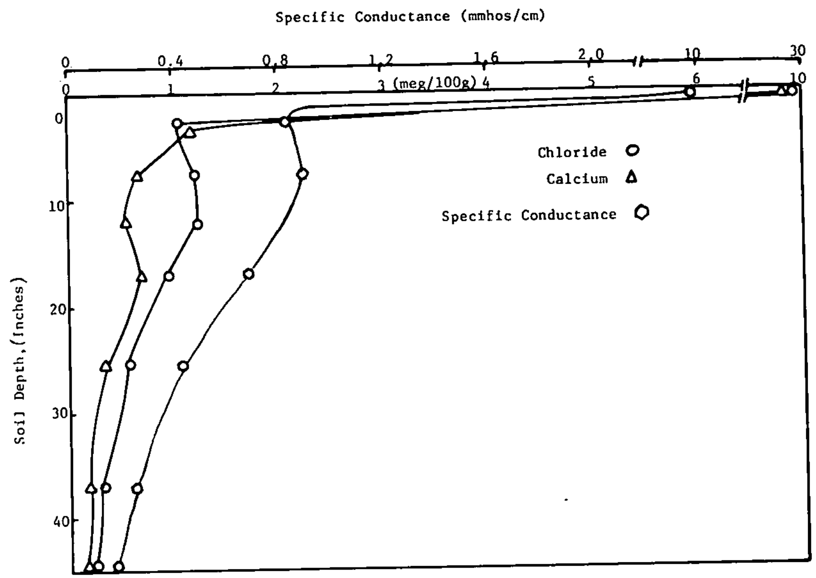

Figure J-9. Specific conductance as well as chloride and calcium concentrations in a Sassafrass soil in June 1968. Calcium chloride was applied on the surface the previous winter. (Warsaw, Va.)

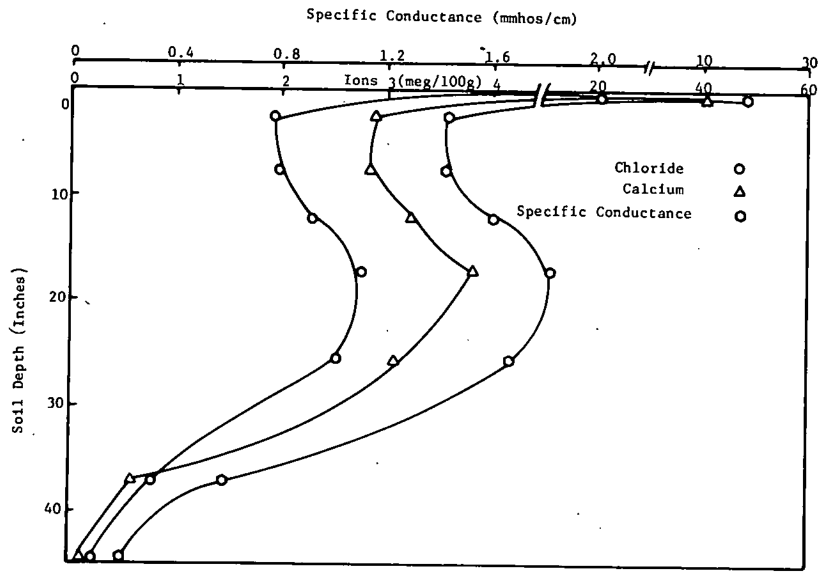

Figure J-10. Specific conductance as well as chloride and calcium concentrations in a Groseclose soil treated with sodium chloride at 1,500 lb per acre (Warsaw, Va., June 1968).

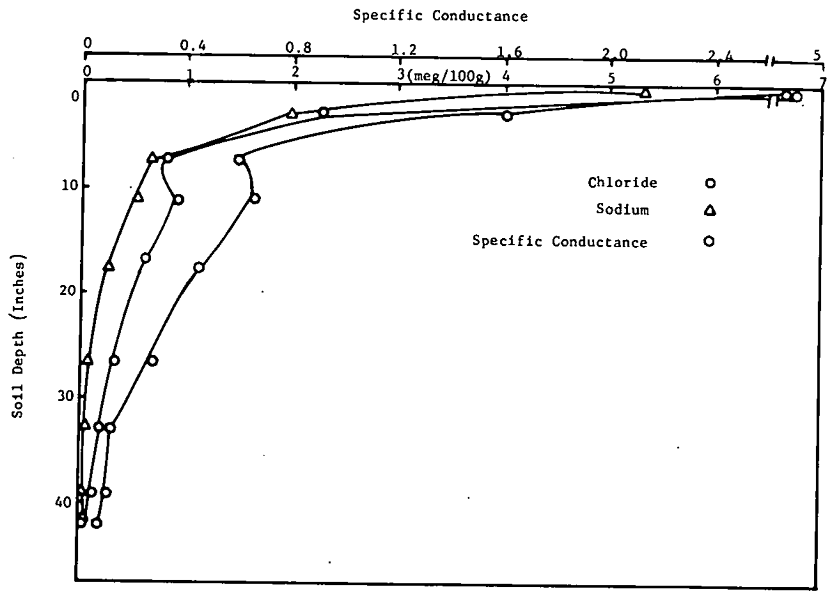

Figure J-11. Specific conductance as well as chloride and sodium concentrations in a Groseclose soil treated with sodium chloride at 1,500 lb per acre (Blacksburg, Va., June 1968).

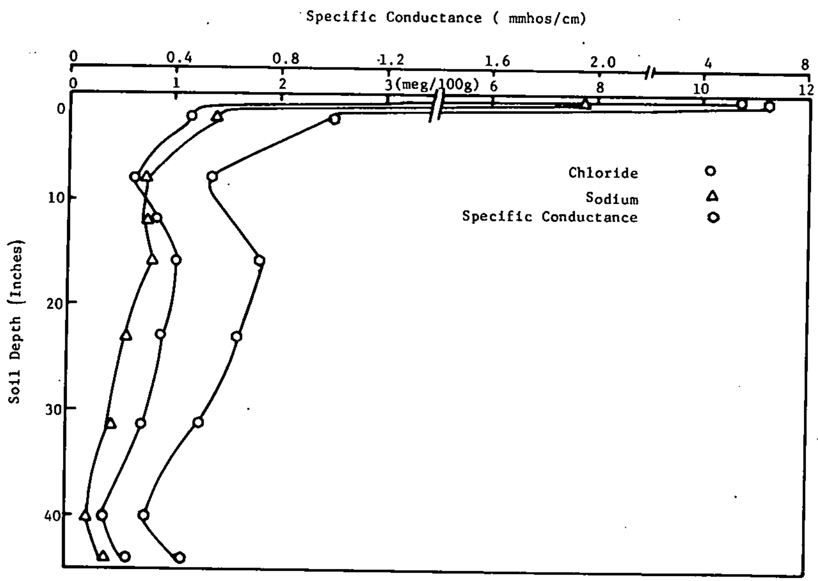

Figure J-12. Specific conductance as well as chloride and sodium concentrations in a Groseclose soil treated with sodium chloride at 6,000 lb per acre (Blacksburg, Va., June 1968).

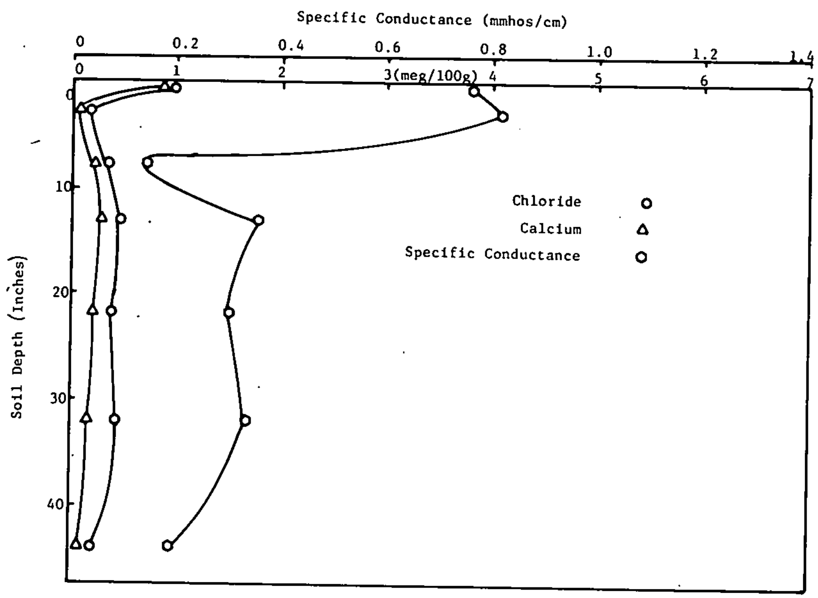

Figure J-13. Specific conductance as well as chloride and calcium concentrations in a Groseclose soil treated with calcium chloride at 1,500 lb per acre (Blacksburg, Va., June 1968).

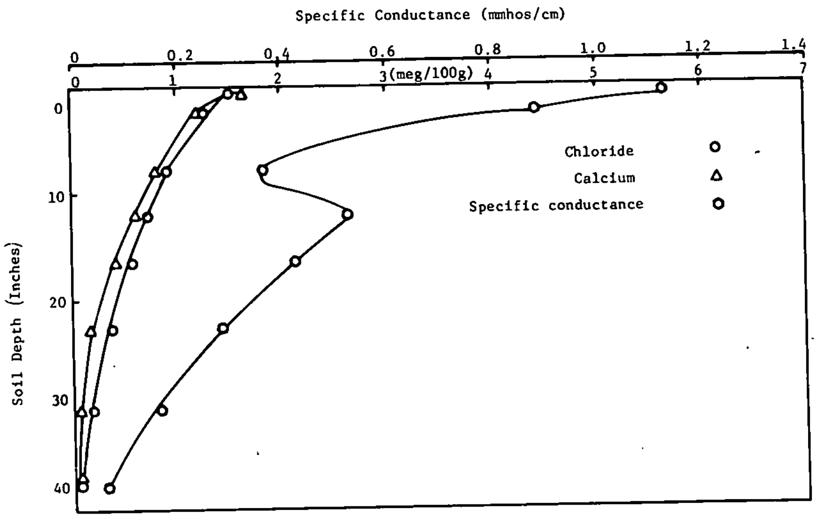

Figure J-14. Specific conductance as well as chloride and calcium concentrations in a Groseclose soil treated with calcium chloride at 3,000 lb per acre (Blacksburg, Va., June 1968).

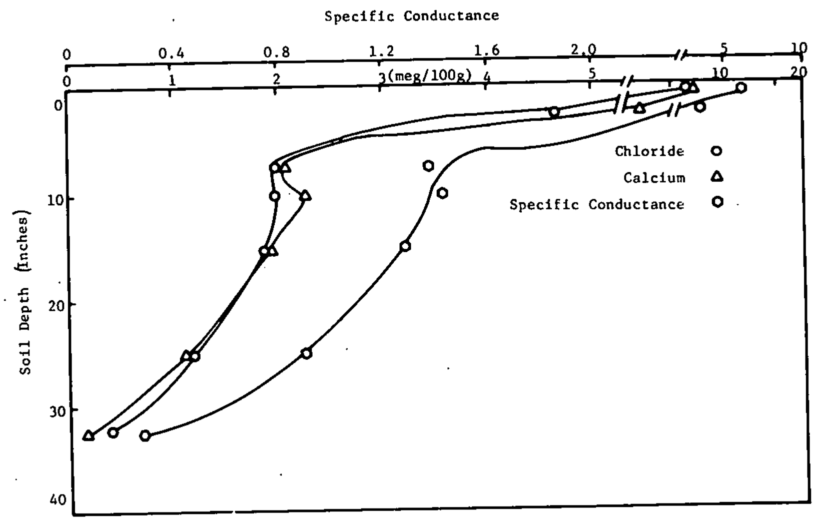

Figure J-15. Specific conductance as well as chloride and calcium concentrations in a Groseclose soil treated with calcium chloride at 6,000 lb per acre (Blacksburg, Va., June 1968).

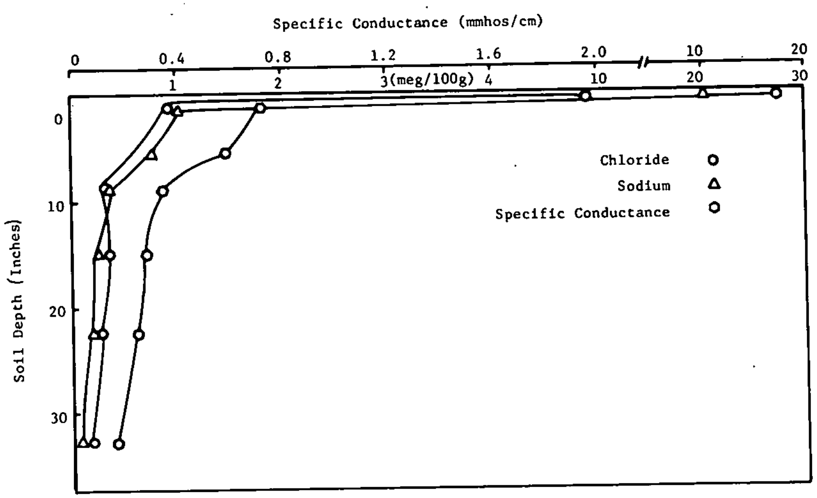

Figure J-16. Specific conductance as well as chloride and sodium concentrations in a Nason soil treated with sodium chloride at 1,500 lb per acre (Orange, Va., June 1968).

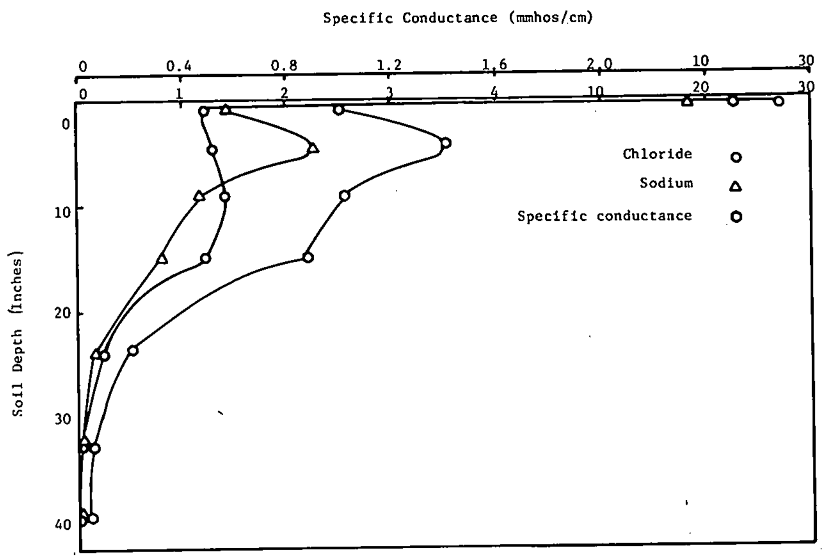

Figure J-17. Specific conductance as well as chloride and sodium concentrations in a Nason soil treated with sodium chloride at 3,000 lb per acre (Orange, Va., June 1968).

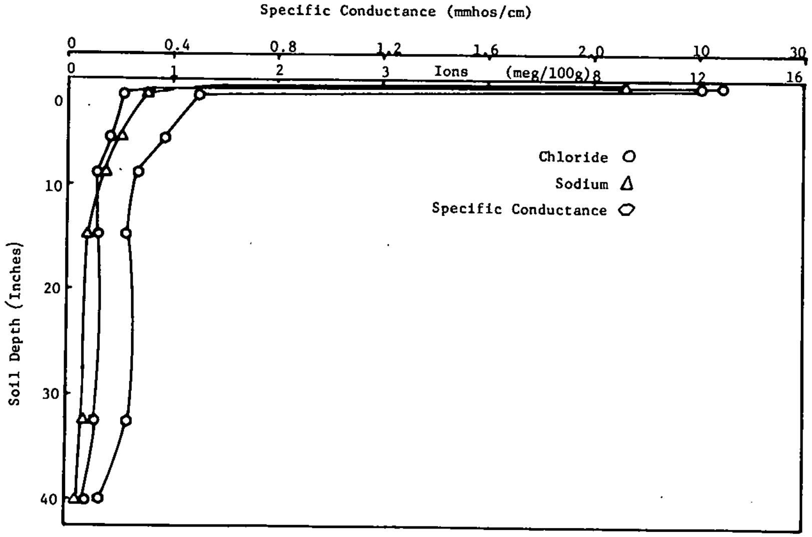

Figure J-18. Specific conductance as well as chloride and sodium concentrations in a Nason soil with sodium chloride at 6,000 lb per acre (Orange, Va., June 1968).

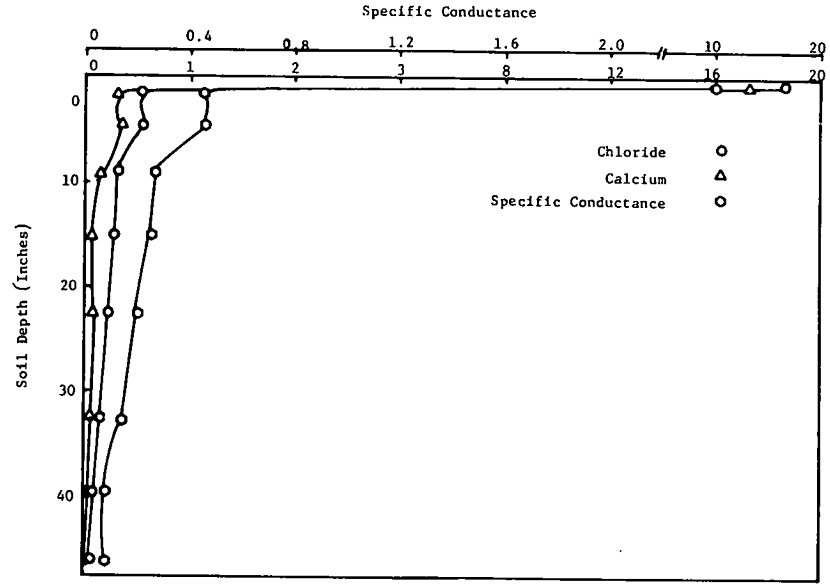

Figure J-19. Specific conductance as well as chloride and calcium concentrations in a Nason soil treated with calcium chloride at 1,500 lb per acre (Orange, Va., June 1968).

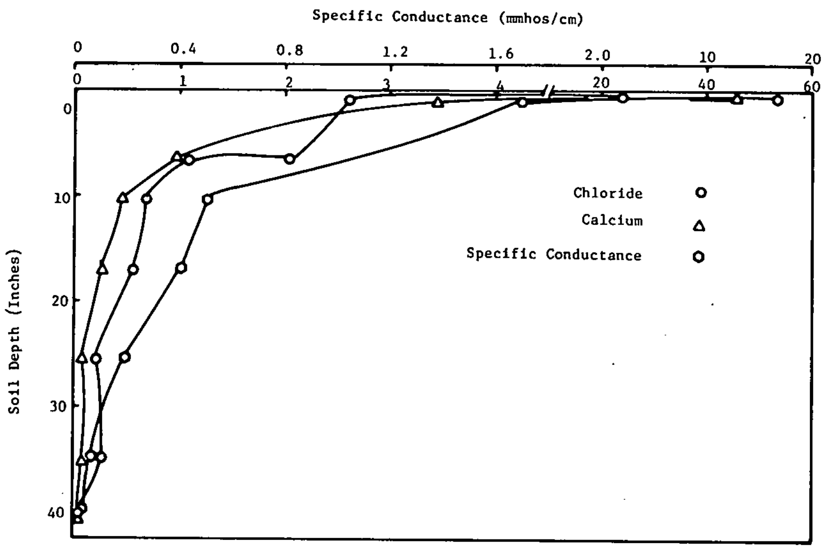

Figure J-20. Specific conductance as well as chloride and calcium concentrations in a Nason soil treated with calcium chloride at 3,000 lb per acre (Orange, Va., June 1968).

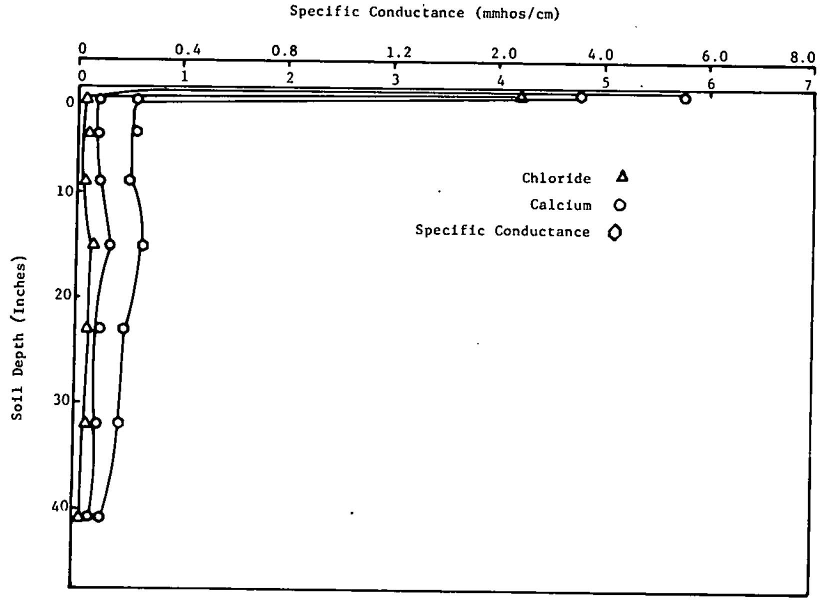

Figure J-21. Specific conductance as well as chloride and calcium concentrations in a Nason soil treated with calcium chloride at 6,000 lb per acre (Orange, Va., June 1968).

the soil profile than did the NaCl. In the Sassafras soil (Fig. J-22), the specific conductance for $CaCl_2$ salt applications was much higher than for NaCl, especially in the upper portion of the profile. The chloride concentration was also greater for $CaCl_2$ than the NaCl deicing salt (Fig. J-23). The lower conductance values and chloride for NaCl treatments in the upper profile, and the greater values in the lower profile, are better illustrated for the Groseclose (Figs. J-24 and J-25) and Nason soils (Figs. J-26 and J-27). Calcium, a divalent cation, is held tight on the soil exchange complex compared to sodium and this apparently accounts for the slower movement.

TABLE J-2

SPECIFIC CONDUCTANCE AND CHLORIDE, SODIUM, AND CALCIUM CONCENTRATIONS IN THREE SOILS WITHOUT DEICING SALT APPLICATIONS

DEPTH (IN.)	SPECIFIC CONDUCTANCE (MMHO/CM)	Cl (MEQ/100 G SOIL)	Na	Ca
		Sassafras		
0 to 1/2	0.255	0.039	0.087	0.142
1/2 to 5	0.076	0.003	0.013	0.049
5 to 10	0.079	0.004	0.013	0.034
10 to 14	0.041	0.003	0.013	0.020
14 to 20	0.039	0.004	0.013	0.017
20 to 31	0.043	0.013	0.013	0.017
31 to 42	0.036	0.004	0.008	0.015
42+	0.036	0.004	0.008	0.010
		Groseclose		
0 to 1/2	0.137	0.013	0.014	0.072
1/2 to 6	0.074	0.004	0.018	0.064
6 to 10	0.075	0.005	0.018	0.060
12 to 20	0.051	0.014	0.016	0.034
20 to 28	0.043	0.011	0.010	0.025
28 to 36	0.035	0.006	0.008	0.016
36 to 40	0.027	0.009	0.011	0.007
40+	0.018	0.001	0.008	0.002
		Nason		
0 to 1/2	1.012	1.211	0.736	0.024
1/2 to 4	0.179	0.127	0.146	0.042
4 to 8	0.181	0.146	0.169	0.040
8 to 12	0.108	0.099	0.087	0.037
12 to 18	0.092	0.086	0.062	0.030
18 to 24	0.070	0.075	0.045	0.037
24 to 30	0.076	0.083	0.038	0.014
30 to 36	0.029	0.021	0.016	0.002
36 to 44	0.034	0.032	0.024	0.059

The movement of the deicing salts in the soils was associated with time, in the sense that time is related to the amount of rainfall and leaching to lower soil depths. In time, with sufficient rainfall, both of these deicing salts will be completely removed from the soil. Figures J-28, J-29, and J-30 indicate that the 6,000-lb-per-acre NaCl treatment applied in 1967 was leached from the Sassafras soil by April 1970. Measures of specific conductance and chloride and sodium concentrations all showed essentially the same leaching patterns of the salt ions. The 6000 lb per acre $CaCl_2$ applied at the same time had also disappeared by April 1970 as a result of leaching by natural rainfall (Figs. J-31, J-32, and J-33). Again, very good agreement was found between calcium and chloride concentrations and the specific conductance values.

NaCl, applied at high rates such as those used in these short-time studies, did not appear to have adverse effects on soil structure to impede internal drainage. The acid soils, formed in the humid regions, have aluminum and iron groups on the exchange complex. These chemical groups are difficult to remove from the soil complex. Removal of these chemical groups is necessary to influence soil particle dispersion to influence soil structure. Thus, it is apparent that under natural leaching conditions the NaCl did not replace the high-charge cation groups, at least not to the extent to cause clay dispersion to block natural internal drainage of soils. However, salt applications over prolonged periods could cause clay dispersion to impede drainage, after which salts would accumulate in soils.

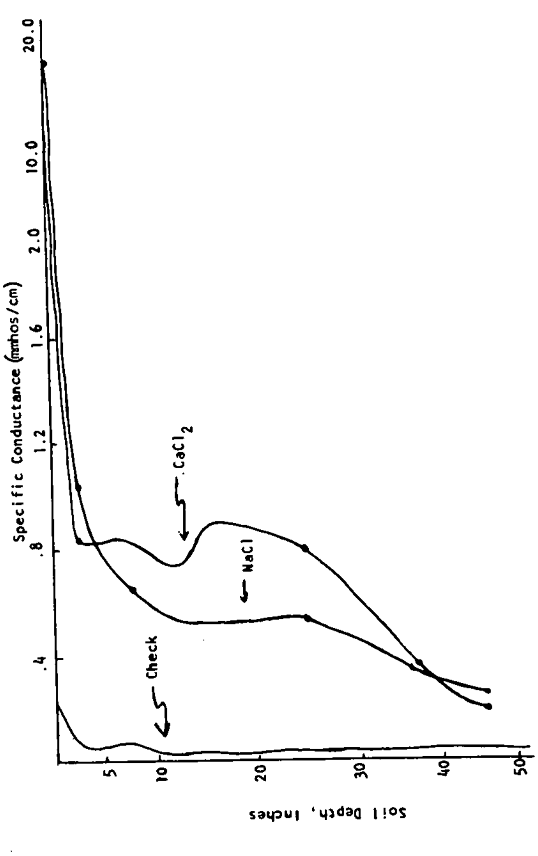

Figure J-22. Specific conductance of water extracts from various depths from a Sassafras soil treated with sodium chloride or calcium chloride (Warsaw, Va., June 1968).

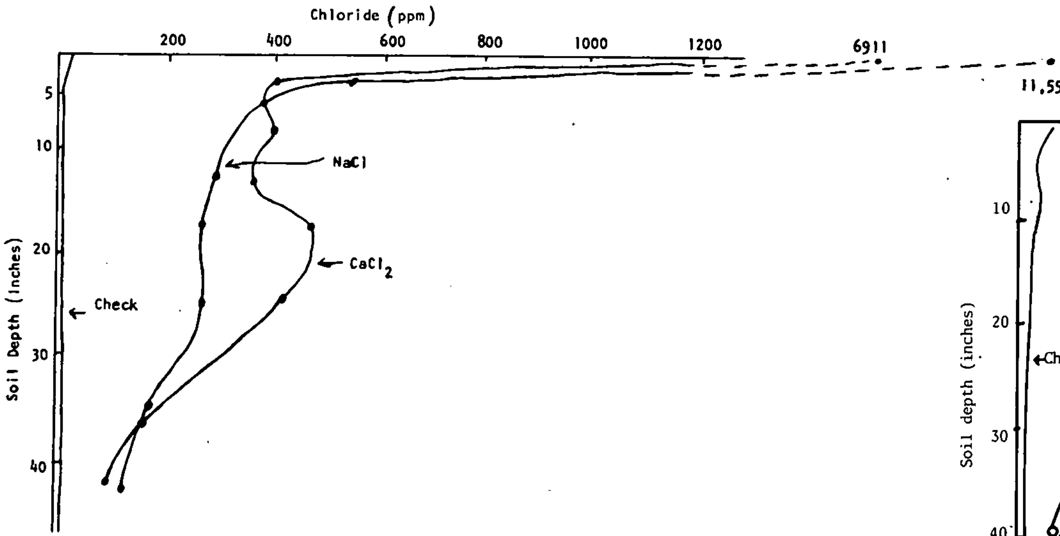

Figure J-23. Average chloride concentrations with depth in a Sassafras soil when applying sodium chloride or calcium chloride (Warsaw, Va., June 1968).

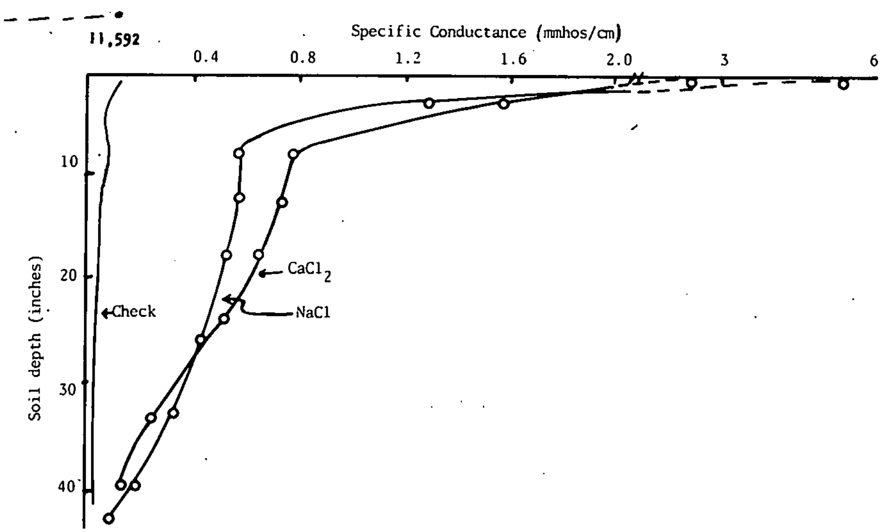

Figure J-24. Specific conductance of water extracts from a Groseclose soil treated with sodium chloride and calcium chloride (Blacksburg, Va., June 1968).

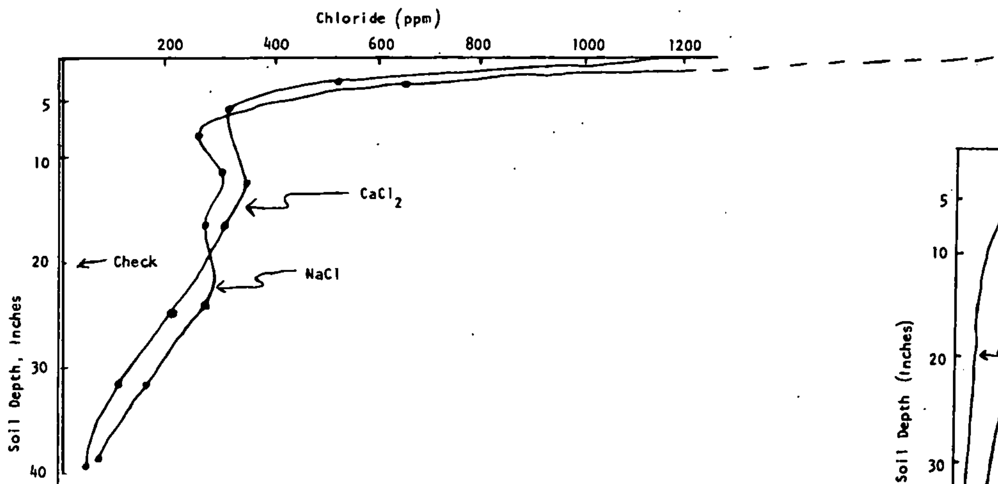

Figure J-26. Specific conductance of water extracts from Nason soil treated with sodium chloride or calcium chloride (Orange, Va., June 1968).

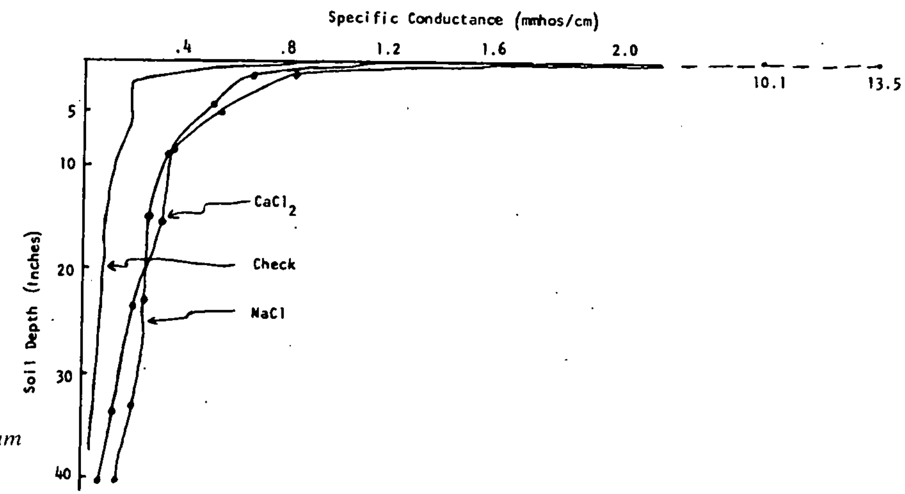

Figure J-25. Average chloride concentrations with depth in Groseclose soil for sodium chloride and calcium chloride (Blacksburg, Va., June 1968).

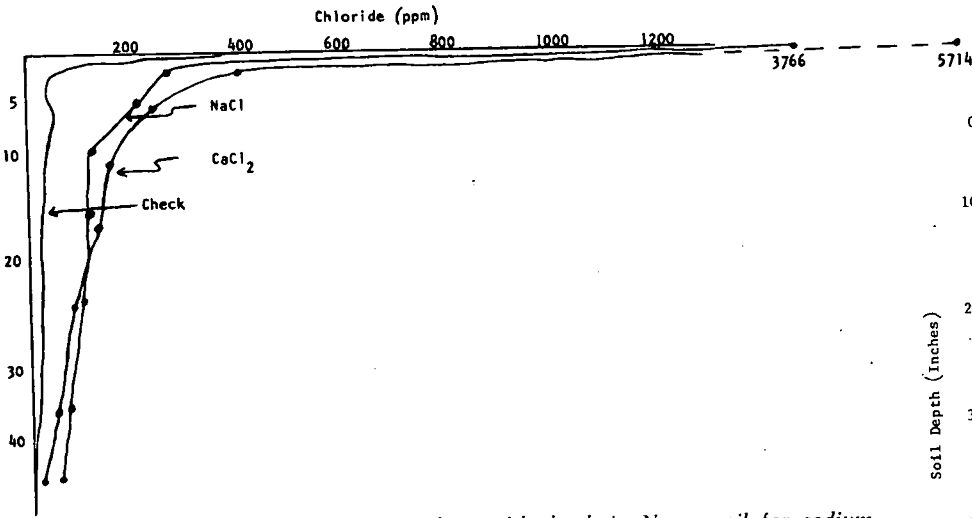

Figure J-27. Average chloride concentrations with depth in Nason soil for sodium chloride or calcium chloride (Orange, Va., June 1968).

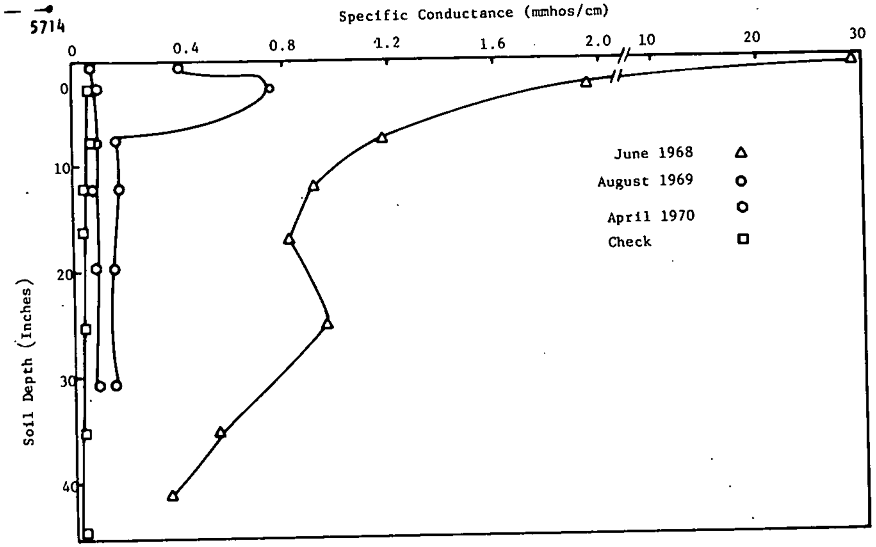

Figure J-28. Specific conductance of water extract from a Sassafras soil at various depths which had been treated with sodium chloride at 6,000 lb per acre in split applications during January, February, and March 1968 (Warsaw, Va.).

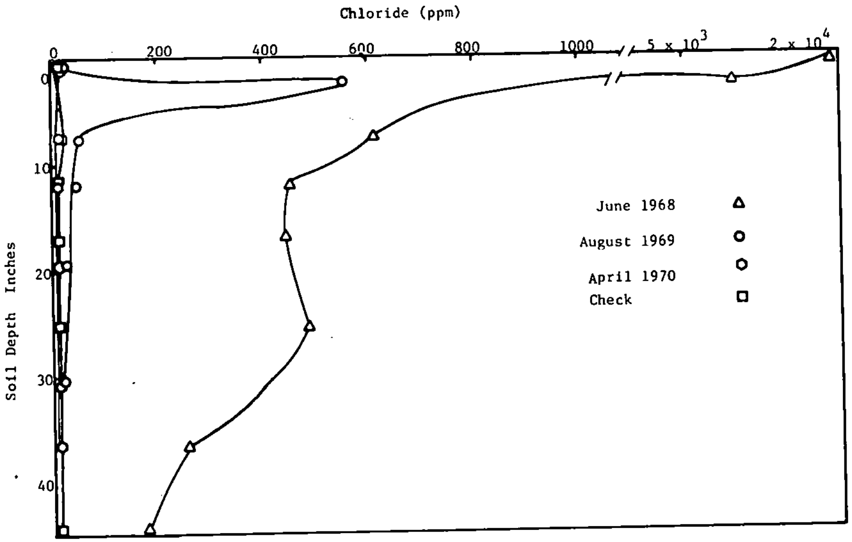

Figure J-29. Chloride concentrations in Sassafras soil at various depths from applications of sodium chloride at 6,000 lb per acre in split applications during January, February, and March 1968 (Warsaw, Va.)

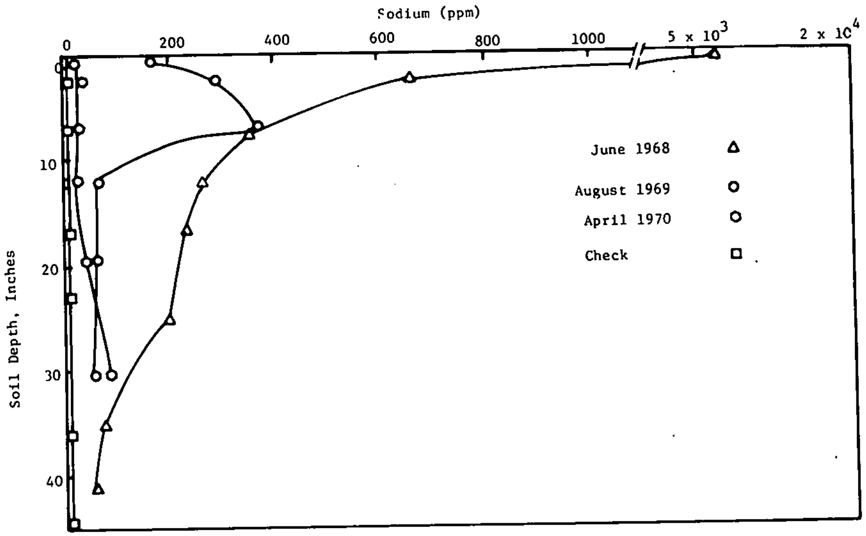

Figure J-30. Sodium concentration in Sassafras soil at various depths from applications of sodium chloride at 6,000 lb per acre in split applications during January, February, and March 1968 (Warsaw, Va.).

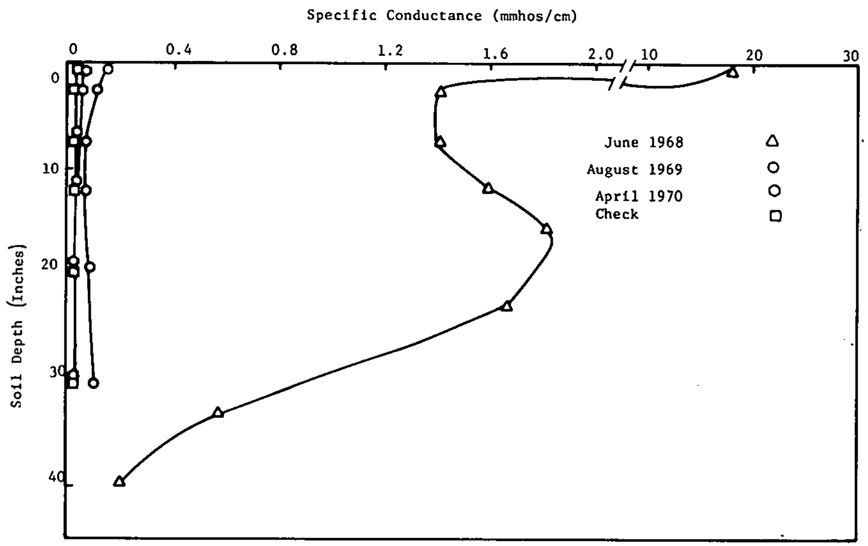

Figure J-31. Specific conductance of water extracts from a Sassafras soil at various depths which had been treated with calcium chloride at 6,000 lb per acre in split applications during January, February, and March 1968 (Warsaw, Va.).

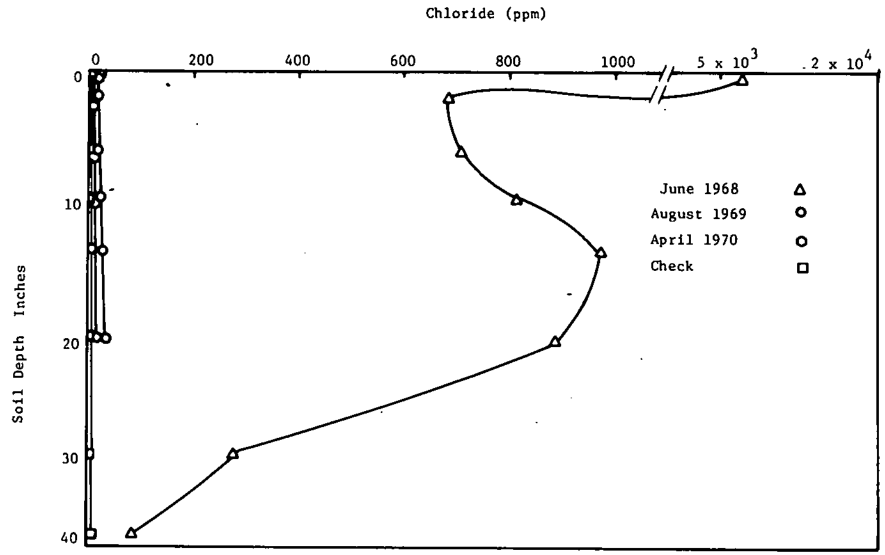

Figure J-32. Chloride concentration in Sassafras soil when treated with calcium chloride at 6,000 lb per acre during January, February, and March 1968 (Warsaw, Va.).

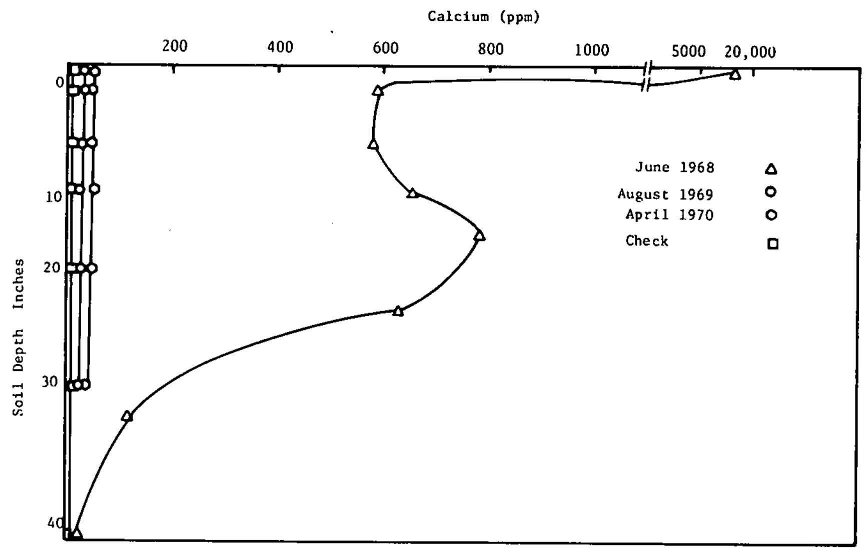

Figure J-33. Calcium concentration in Sassafras soil at various depths which had been treated with calcium chloride at 6,000 lb per acre in split applications during January, February, and March 1968 (Warsaw, Va.).

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