Influence of Deicing Salt on Vegetation, Groundwater, and Soil Along Two Highways in Sweden

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During spring 1994, vegetation damage to a remarkable and previously unknown extent was observed along many heavily used roads in southern Sweden. An investigation was conducted to determine the cause of vegetation damage along Highways E20 and 48 by performing a damage survey and measurement of sodium and chloride concentrations in pine and spruce needles, groundwater, and soil. At the same time, changes in salt concentration in groundwater and soil in two previously studied areas close to E20 were documented. The extensive damage to vegetation probably can be attributed to three interacting factors: the large amount of deicing salt applied during the winter of 1993–1994, the lateness of the last salting, and the hot, dry weather during the budding season. This conclusion is supported by the damage observations and the very high sodium and chloride concentrations in pine and spruce needles along the roads. In extreme cases, the sodium concentration was >1,000 ppm (dry weight) in current-year needles and >5,000 ppm in needles from the previous year. The concentrations decreased rapidly with increasing distance from the road and, similarly, the needles in branches turned toward the road had higher salt concentrations than needles in branches turned in other directions. The groundwater and soil from an area along E20 showed greatly increased sodium and chloride concentrations, especially next to the road, compared with previous measurements. The increased concentration can be explained only by the increase in road salting.

During early summer 1994, extensive damage to vegetation was observed along heavily used roads in large parts of southern and central Sweden, including clear signs of damage along Highways E20 and 48 in Skaraborg County. It was suspected even at an early stage that the damage was the result of road salting.

During the late 1970s, the Swedish National Road and Transport Research Institute (VTI) had carried out a study of the environmental influence of road salt based on seven observation areas in Skaraborg County where samples of soil, groundwater, and vegetation were taken. The areas were followed from spring 1978 to autumn 1979. The results showed increased salt concentrations in several areas resulting from the use of road salt (*1*).

To study the long-term effects of winter road salting, VTI performed further sampling of groundwater and soil in 1988 in three of the observation areas but limited the samples to groundwater and soil. The results indicated that one area continued to be largely unaffected by salting, another showed a further increase in already high salt concentrations, and the third had an unchanged high level of salt concentrations (*2*).

The purpose of the present investigation was to identify the causes of vegetation damage along Highways E20 and 48 in Skaraborg County by using damage inspections and sodium and chloride analysis of conifer needles, groundwater, and soil. In addition, changes in salt concentrations in groundwater and soil in two previously investigated areas along E20 were documented (*3*).

Winter Salting and Meteorological and Hydrological Conditions

In comparison with earlier years, road salt consumption by the Swedish National Road Administration (SNRA) was very high in winter 1992–1993 and especially in winter 1993–1994, both in Skaraborg County and in Sweden as a whole (Table 1). In spring 1994, the last salt applications on E20 took place relatively late, March 25 and April 3.

E20 has an average daily traffic of 5,000 to 8,500 vehicles, with a large proportion of heavy vehicles (15 to 20 percent). In the particular area, the period April through May 1994 was dry and precipitation was 47 to 55 percent of normal. The temperature was unusually high for 4 to 5 weeks beginning on April 22. During April, the groundwater level in the county was almost normal, unlike in areas to the north and south, where the groundwater level was higher than normal. In May, the groundwater level was lower than normal.

Field Methods

Needle Sampling

The extent and character of the vegetation damage along Highways E20 and 48 were inspected in the beginning of June 1994. The damage was discussed with SNRA personnel and several university experts. In June samples of current-year needles and the previous year's needles on Scotch pine and Norway spruce twigs were collected. This included sampling at two earlier VTI sampling areas, R4 and R6. The samples were taken at various distances from the road, various heights above the ground, and various orientations to the trunk. Sampling also was performed on two spruce hedges, one parallel to Highway E20 and one perpendicular to it.

The distance from the road was measured from the edge of the asphalt. Unless otherwise specified, samples were taken from twigs about 2 to 3 m above the ground.

TABLE 1 Salt Consumption (Tonnes) by the Swedish National Road Administration

	Skaraborg County	All Sweden
Winter 1991/92	24,000	210,000
Winter 1992/93	26,000	330,000
Winter 1993/94	31,000	420,000

Groundwater and Soil Sampling

Sampling of groundwater and soil was performed in two previously established observation areas on E20 between Götene and Mariestad.

At one of the areas (R4), the road is built on a low embankment and consequently there are no proper ditches. The area is bordered to the east by a stream. The clay in the area is covered by a comparatively thin (1.0 to 1.5 m) layer of fine-medium sand. The groundwater level is mostly high, although during dry periods it may fall below the level of the sand layer. The groundwater flows slowly toward the northeast, parallel to the road. Since the road's longitudinal profile also slopes toward the northeast, the area receives water from a relatively long stretch of the road immediately to the southwest.

The other area (R6) is level with the road, from which it is separated only by a normal ditch. Geologically, the area resembles Area R4, with a relatively thin layer of fine-medium sand overlying clay. Unlike Area R4, however, the sand layer contains more medium sand, which probably makes the layer somewhat more permeable to water. During spring and autumn, the groundwater level is high, about 0.5 m below the ground surface. In dry periods during the summer, however, the groundwater level may fall below the level of the sand layer. The groundwater flows in a westerly direction from the road.

During spring 1978, groundwater pipes were installed in the two areas. The perforation in the pipes was 0.5 to 1.5 m below the ground level, in the sand layer. Sampling of the groundwater was performed in the beginning of June 1994. The groundwater levels were then very low, and sampling was therefore not possible in all pipes. Soil sampling was performed in the beginning of July 1994. Samples were taken from two to four levels down to 165 cm below ground level close to each groundwater pipe. Samples were taken only in the sand layer because it was likely that fossil water, which originated in the early development of the Baltic Sea, could occur in the underlying clay.

Results

General Damage in Area

A majority of the trees and bushes along both E20 and 48 in Skaraborg County showed clear signs of damage. The damage appeared on most species of trees and bushes, both in gardens and in agricultural and forested areas. It took the form of bare or dead branches, twigs, or shoots; lack of emerging shoots during the late spring; red-brown pine needles from the previous year; and generally sparse foliage. The damage was by far the most pronounced in the immediate vicinity of the road. Trees and bushes nearest the road showed the most severe damage. There was no difference in vegetation damage on the two sides of the road. In the woods, the damage decreased rapidly with increasing distance from the road, particularly in dense stands. At sites with sparse stands or isolated trees or bushes, or where insufficient shelter was provided by other trees, the damage also appeared at greater distances from the road (at least 50 m). The damage thus was closely related to exposure to the road. Similarly, noise barriers appeared to provide good protection; often, the part of the tree exposed above the barrier showed clear signs of damage while the sheltered part of the tree was relatively undamaged.

Visible Damage to Coniferous Trees

On small pine trees very close to the road, all the foliage was often red-brown, sometimes with the exception of the top shoot. On somewhat less-exposed pines and on older pines, damage usually occurred only on branches facing the road. Similarly, lower branches were often more damaged than upper branches, the top shoot being completely unaffected.

On exposed pine branches, the current-year shoots had often completely failed to emerge, especially where the previous year's needles were red-brown. However, it was not unusual for shoot formation to have taken place from branches whose previous year's needles were completely red-brown and which had no older needles.

Remarkably enough, the spruce showed a different damage image. Close to the road, small spruces and exposed branches of larger trees generally lacked needles from previous years, but these branches had to a large extent succeeded in producing shoots in 1994. On fresh spruce shoots from the current year, the young needles had a healthy, bright green color. Because of these bright green current-year shoots, the spruces near the road left a relatively healthy impression on a superficial inspection. It should be noted that the striking bright green color of the growing needles distinguished the spruce from the pine, whose new shoots had a dark green color from the beginning. Another factor that strongly influenced the difference in visual impression between the species was that the red-brown needles from the previous year were still in place on the pine trees, while the spruce trees had already shed their dead needles.

Introduced coniferous species such as cypress, arborvitae, and others also had been damaged. However, damage in gardens was not registered systematically.

Visible Damage to Deciduous Trees and Bushes

In gardens and elsewhere along the roads, extensive damage was observed in nearly all species of deciduous trees and bushes. The damage appeared mainly as sparse foliage, dried-up twigs, twigs that had produced no buds, and failure to flower.

Salt Concentrations in Needles

In every case, needles from the previous year had many-times-higher sodium concentrations than needles from the current year, in both high and low salt loading. The chloride concentrations were, however, more similar between the different year growths of needles; often, the previous year's needles showed higher concentrations than the current year's needles, although seldom more than twice as high.

Samples taken close to the road showed heavily increased sodium and chloride concentrations both in needles from the current year and in those from the previous year (Figures 1 and 2). The chloride concentration was greatly increased within about 10 to 30 m of the road, but the concentration was on the same level at a distance of 48 m as at 98 m. Even at 98 m, the chloride concentration showed a certain increase compared with normal concentrations according to the literature. However, it should be added that the studied area lies only 120 to 180 km from the sea and that salt can be transported long distances by the wind.

A tall spruce tree showed a large increase in concentration of both sodium and chloride in the lowermost branch and a certain increase in sodium concentration in the previous year's needles up to a height of 9 m.

With few exceptions, the needles on branches facing the road had many-times-higher concentrations of both sodium and chloride compared with branches facing

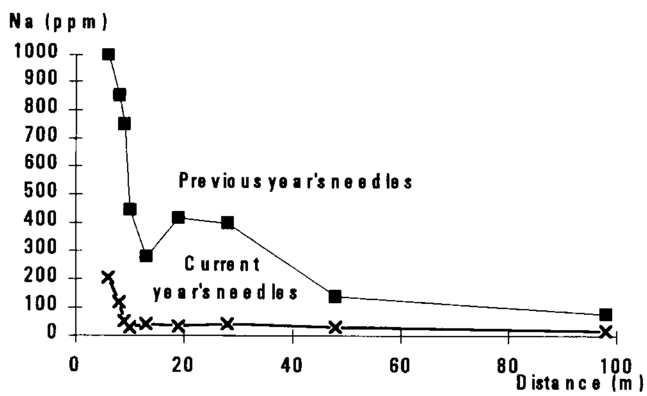

FIGURE 1 Concentrations of sodium in needles from pine trees at various distances from Highway E20, ppm = μg (g dry weight)$^{-1}$.

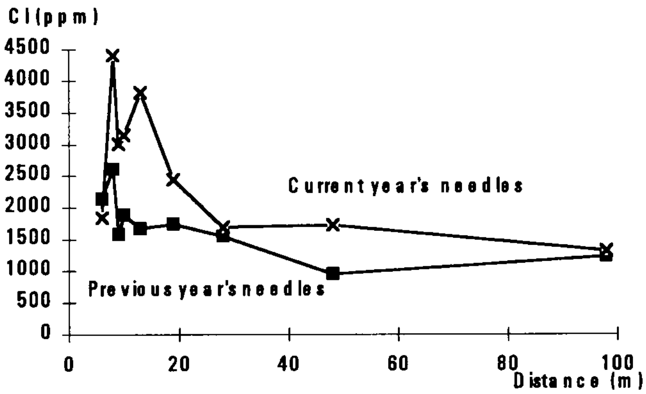

FIGURE 2 Concentrations of chloride in needles from pine trees at various distances from Highway E20, ppm = μg (g dry weight)$^{-1}$.

away from the road. That a dense spruce hedge along the road can offer effective protection is shown by the low sodium and chloride concentrations in needles on the lee side of the hedge compared with the high concentrations in needles on twigs facing the road, which showed extensive damage (Table 2).

In needles from extremely exposed trees, very high concentrations were recorded: for sodium sometimes more than 1,000 ppm in the current year's needles and 5,000 ppm in the previous year's needles, and for chloride sometimes more than 8,000 ppm in both years' needles. In previous-year brown needles of a dying pine, the sodium concentration was 1.7 percent and the chloride concentration, 2 percent.

Salt Concentrations in Groundwater and Soil

Compared with the earlier samplings, the sodium and chloride concentrations in Area R4 were greatly increased in 1994 both in the groundwater and in the soil samples (Figure 3). The concentrations were increased at all sampling points, but the greatest increases were measured in those points nearest the road. The concentrations also showed a clear relationship to distance from the road.

The sodium and chloride concentrations in Area R6 in 1994 mainly remained at the relatively high levels measured earlier—no significant increase in concentrations was observed (Figure 4). At the two sampling points nearest the road, the concentrations were highest at a level 0.5 m below the ground surface.

Discussion

Vegetation

Vegetation Damage Along Roads

Nearest the road, the vegetation generally is exposed to severe conditions as a result of several interacting stress factors. In many cases, this may lead to a generally weakened condition, predisposing the vegetation close to the road to damage from exhaust emissions, road salt, and other pollutants, as well as to attack by pathogens (fungi) of various types.

Damage to Coniferous Trees

The observed damage to the conifers was clearly of a physiological nature. The red-brown color, often of the whole needle but initially at its tip, is typical of drying out as a result of salt. Salt accumulation can produce rapid discoloration and die-back of needles.

On the other hand, it is probable that the pollution load in combination with unfavorable meteorological conditions causing frost drought or water stress during previous years may have weakened those trees that showed damage in 1994. During spring and early summer 1993, the spruce trees were exposed to severe frost drought on a large scale in southern Sweden, including Skaraborg county. In many cases, the lack of previous year's needles observed during early summer 1994 may be attributed to frost drought during spring 1993.

Sodium and Chloride Concentrations in Needles

According to the literature, the sodium concentration in pine and spruce needles is normally between 50 and 200 ppm (microgram per gram dry weight) and some-

TABLE 2 Sodium and Chloride Concentrations in Needles from a Spruce Hedge on E20, μg (g Dry Weight)$^{-1}$

Side of the hedge	Na Previous year's needles	Na Current year's needles	Cl Previous year's needles	Cl Current year's needles
Facing road	744	62	4280	2200
Facing garden	358	28	2470	1370

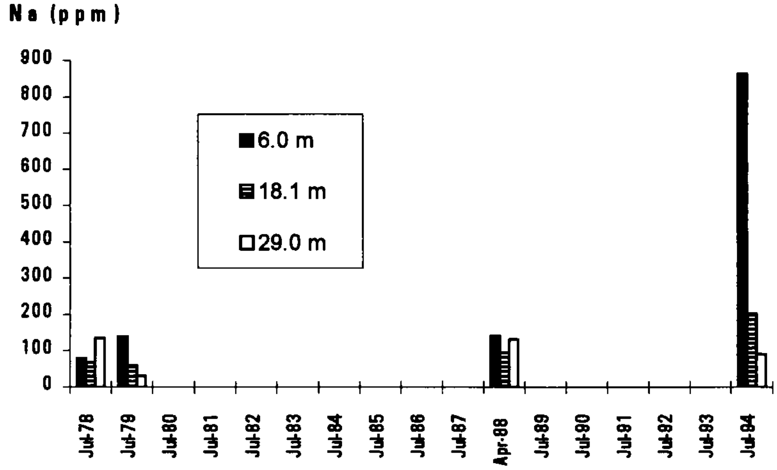

FIGURE 3 Sodium concentrations in soil (0 to 15 cm depth) sampled at various distances from edge of pavement, Area R4 on Highway E20.

times up to 1,000 ppm (*4*). This probably applies to needles from the previous year and before. In the samples of previous year's needles analyzed here, sodium concentrations lower than 200 ppm were observed only in a spruce tree 98 m from the road, in the spruce hedge at a distance of 38 m from the road, in two pine trees 48 m and 98 m from the road, respectively, and in a pine branch 19 m above the ground. In the investigations carried out in 1978 and 1979 along the particular section of E20, the background concentration in the previous year's needles was about 60 to 80 ppm (*1*). The highest concentrations recorded in the present investigation, several thousand parts per million, must be considered very high. Needles on small, dying trees had concentrations of more than 4,000 ppm and in completely brown pine needles 17,000 ppm was recorded. In the investigations carried out in 1978 and 1979, it was found that trees with sodium concentrations of more than 5,000 ppm in needles regularly showed damage in the form of dying needles and branches (*1*).

In the case of salt damage, the chloride ion is considered more indicative than the sodium ion. The extent of visible vegetation damage is often stated to be closely related to the chloride concentration in the tissues. In the literature, needles (probably the previous year's needles and older needles) are stated normally to have chloride concentrations of 500 to 800 (to 1,300) ppm. Concentrations greater than about 2,500 to 3,500 ppm are considered toxic. Other information indicates 4,000 to 6,000 ppm as a lower limit for the occurrence of damage. In one investigation, the needles on dying spruce trees proved to have chloride concentrations of 4,500 to 10,000 ppm. An investigation of coniferous trees influenced by salt in highway storm water revealed chloride concentrations of 13,000 to 15,000 ppm in damaged spruce trees, while undamaged spruce trees had concentrations below 1,500 ppm. For current year's needles on spruce trees, a long-term investigation gives 3,000 ppm as the lower limit for the occurrence of road salt damage. Spruce is stated to be somewhat more sensitive to

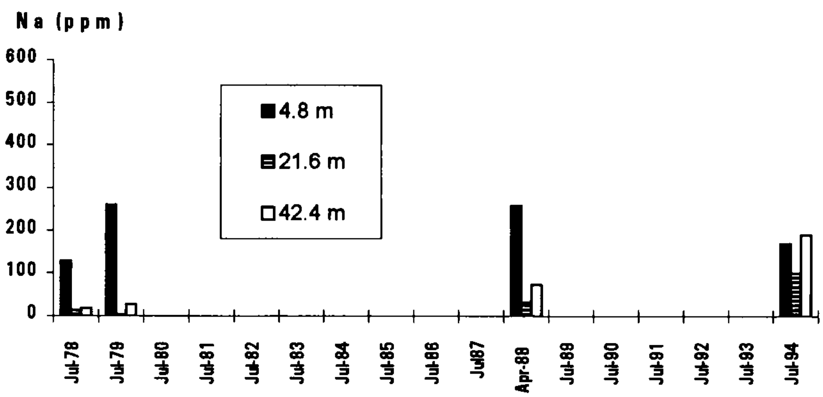

FIGURE 4 Sodium concentrations in soil (0 to 15 cm depth) sampled at various distances from edge of pavement, Area R6 on Highway E20.

salt than pine. Similarly, coniferous trees, which are evergreen, are generally stated to be more sensitive to salt damage than are deciduous trees (*4*).

Damage to Deciduous Trees

Damage to deciduous trees in the survey area was to a remarkable and previously unknown extent. The damage to deciduous trees that appeared in 1994 was, as in the conifers, probably the result of a combination of salt load and other stress factors over a series of years. Birch trees were probably weakened by drought stress following very hot, dry weather during spring and early summer of 1993 and particularly 1992.

Foliar Uptake or Root Absorption

The sodium and chloride ions in salt can reach the leaves or needles both by foliar uptake and by root absorption. The fact that needle discoloration and lack of shoot formation in the present study were clearly limited to the most exposed branches and twigs indicates that transport took place mainly through direct spray and aerosol deposition on the foliage, and that root absorption did not play a major part, at least in the rapid damage. In root absorption, the damage would not have been so clearly limited to the directly exposed branches and twigs.

Even if the observed damage is probably more attributable to direct deposition on the foliage than to root absorption, it cannot be excluded that unfavorable soil conditions, such as salt stress and drought, during earlier periods may have weakened the vegetation and made it predisposed to damage. Salt influence via the roots during a long series of years may thus have contributed to a deterioration of the tree's growth conditions.

Road Salting and Weather

In addition to the quantity of salt applied, the timing and the weather conditions are stated to be among the most important factors controlling the occurrence of salt damage along roads (*4*). It is likely that one of the main causes of vegetation damage was both that salt application in the area during the winter of 1993–1994 was high and that salting was carried out relatively late in the season. The hot, dry weather during the period of bud swelling, bud unfolding, and shoot formation probably contributed greatly to the occurrence of damage, or at least aggravated it.

Groundwater and Soil

A conclusion from the earlier investigations in the area (1) was that there is no clear and unambiguous relationship between the salt quantities spread on the road and the salt concentrations occurring in the surrounding natural environment. A certain quantity of salt thus may give rise to high concentrations in soil and groundwater in one area, while the same quantity of salt would lead to no observable salt increase in another area. The geological and hydrological conditions determine the extent to which an area is affected by salt pollution.

Both investigated sites on E20 (R4 and R6) are considered to have unfavourable hydrogeological conditions with permeable surface soil layers, high groundwater levels, and very poor water renewal rates (flat topography). This is confirmed by the raised salt concentrations in soil and groundwater throughout the follow-up period (1978 to 1994).

It is difficult to determine with certainty why Area R4 appeared to be considerably more influenced than Area R6 in 1994. A contributory cause is that Area R4 receives salt from a considerably longer section of road. The somewhat more permeable soil layers in Area R6 may also contribute to transporting the incoming quantities of salt away more quickly. Another possible explanation is differences between the two areas in the salt quantities applied over the years.

It is worth noting that both R4 and R6 are located in a low-lying area that was covered by sea water after the latest deglaciation. The fine-grained sediments (principally clays) deposited in this salt water still contain considerable quantities of salt. As a result, the area has a relatively large number of salt-polluted wells. However, the salt concentrations in soil and groundwater reported here are not considered to be influenced by these conditions because sampling, both of groundwater and soil, was performed only in the sand layers overlying the clay. Because of the permeability and the water renewal rate, it is unlikely that any fossil water of marine origin remains in this layer.

Conclusions and Recommendations

The extent of the vegetation damage clearly shows that damage is related to the road and its traffic. The very high concentrations of sodium and chloride in the needles indicate that road salt plays a decisive, or at least dominating, role in the occurrence of the damage. Direct foliar uptake probably plays a more important role than root absorption in salt transport to the needles. This is supported by two observations—the damage to branches with varying exposure to the road, and the difference in the salt concentration in the needles with varying exposure and height above the ground. That the damage is so great is probably because of three interacting factors: the large quantity of salt applied during the salting season in 1993–1994, the lateness of the last salt application, and the very hot, dry weather during bud unfolding. The large quantity of salt applied during the winter of 1992–1993 probably contributed to the damage that occurred during the spring of 1994. The unusual weather conditions during 1993 may also have had an influence. Growth conditions for the vegetation nearest roads with heavy traffic are often unfavorable. Groundwater and soil showed clearly increased salt concentrations in the two areas studied on E20. The large increase in concentration in one of the areas during the summer of 1994 cannot be explained in any way other than by a large increase in road salting.

To reduce the influence on vegetation, groundwater, and soil nearest the roads, it is important both to minimize total salt consumption and to avoid salting late in the season, that is, during the last few weeks before bud unfolding.

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