EFFECTS OF ROAD DISTANCE AND PROTECTIVE MEASURES ON DEICING NaCl DEPOSITION AND SOIL SOLUTION CHEMISTRY IN PLANTED MEDIAN STRIPS

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Abstract. The deposition pattern of deicing salt and the resulting concentrations in the soil water were determined in planted median strips of two major approach roads with speed restrictions of 70 kmh (43.5 mph) in Copenhagen, Denmark. The objectives were to evaluate the effect of distance from the roadside and to test different straw mat protective measures. Deposition and soil water concentrations of sodium chloride (NaCl) decreased significantly within 2 m (6.6 ft) from the roadside compared to areas farther away. Straw mats mounted like a skirt around the tree stem did not constitute a proper protection against salt spray or splash and high salt concentrations in the soil water. In contrast, protection with straw mats on all sides of the trees resulted in a small but measurable effect. The highest concentrations of NaCl in the soil water were seen during the winter. However, there was a strong tendency of elevated concentrations persisting throughout the subsequent summer, which suggests that serious salt stress exists on the trees during the growing season. We concluded that planting at a distance of more than 2 m from the roadside is more effective than using straw mats in reducing the undesirable effects of salt spray deposition on trees as well as the salt concentration in the soil water.

Key Words. Road salt; deicing salt; salt stress; median strips; protective measures; roadside distance; soil water; deposition.

Deicing on roads and highways has been widely practiced in Europe and North America since the 1960s in order to minimize traffic delays and accidents associated with slippery roads and pavements (OECD 1989). Decline and death of roadside trees have been associated with root uptake of sodium chloride (NaCl) from carriageway runoff or intercepted salt spray on the aerial parts (e.g., Hanes et al. 1976; Herrick 1988; Dobson 1991; Brod 1993; Gibbs and Palmer 1994). Sodium chloride is by far the most frequently used compound to combat icy roads in Denmark (Randrup and Pedersen 1996).

Results from an extensive questionnaire to all Danish counties and local authorities indicated that stress provoked by NaCl is considered the most serious stress factor for Danish urban trees when compared to such other factors as soil drying, compacted soils, insufficient mold/humus, gusts of wind, insufficient drainage, insufficient nutrient supply, and air pollution (Randrup and Pedersen 1998). Plant species differ in their tolerance and response to salt stress, but the symptoms also depend on whether damage is caused by salt contamination of the soil or by deposition directly on the aboveground part of the plant. Deciduous species are by far the most frequently planted tree species along Danish streets and roads. Without leaves, deciduous trees along Danish roads with restricted traffic speed are most likely to tolerate salt stress from the soil environment (Randrup and Pedersen 1996).

Inexpedient spreading of deicing salt to the surrounding environment takes place in four ways: 1) by malfunctioning salting methods causing some of the deicing salt to be spread outside the carriageway, 2) when salt mist or dry salt is air-entrained off the road by passing traffic or by wind, 3) when dissolved or suspended salt runoff enters the soil, or 4) when salt-contaminated snow or slush is blown or pushed into the roadside by snow plows. The predominant way of spreading deicing salt to the environment depends on the local conditions (traffic, wind, road structure, etc.) and the available snow-clearing and salting equipment (Randrup and Pedersen 1996).

In Denmark, new equipment and technology (e.g., wet salting technique and comprehensive ice warning systems) have been introduced since the 1980s (Jaquet et al. 1992) in order to optimize traffic passability and reduce salt usage. Despite these advances, the consumption of deicing NaCl during the last five winter seasons (1993–1994 to 1998–1999) has increased approximately 33% compared to the levels in the late 1980s (Jaquet et al. 1992). During years with cold winters, the total Danish salt application on paved roads has increased to approximately 2 kg/m^2 per year (Randrup and Pedersen 1996).

Several investigations have described the effects of salt damage as affected by greater distances from roads (e.g., Rich 1972; Kreutzer 1974; Wentzel 1974; OECD 1989; Golwer 1991; Burton 1992). In general, the harmful impact decreases with the distance to the road, but the functional patterns as well as the impact on soil and vegetation differ. Since the 1960s, straw mats or similar barriers often have been used by the Danish authorities to enhance the protection of trees and other important plantings against undesirable stress from either soil salt or airborne salt (Hvass 1985). Use of straw mats as protective measures seems to be dominant in Denmark compared to other countries (Randrup and Pedersen 1996). Although straw mats are by far the most-used protective barriers, the mats are constructed differently and vary in material, shape, lining, and other features. Presumably, no previous trials or tests have been performed to measure the efficiency of the barriers.

The objectives of the present study were to examine the effects of different protective measures and to evaluate the effect of distance between roadside and plants on salt spray deposition and soil water concentrations under urban conditions in Denmark.

MATERIALS AND METHODS

Site Characteristics

The study was carried out at planted median strips at the road Kongevejen (KV) and at the road Ravnsnæsvej (RV) in Copenhagen, Denmark, from January 1997 to April 1999. Copenhagen lies in the temperate zone characterized by a mean annual temperature of 7.8°C (48°F), winter temperatures constantly fluctuating around 0°C (32°F), and a mean precipitation of 675 mm (27 in.). The study period was characterized by higher precipitation than normal (700 to 850 mm [28 to 33 in.] in 1997 and 900 to 1,050 mm [35 to 41 in.] in 1998). In addition, the winter temperatures were higher than normal, and there were fewer incidences where the temperature fluctuated around 0°C.

Site characteristics are shown in Table 1. Deicing NaCl has been applied at both localities since the late 1960s. Median strips at both locations consisted of a grass strip demarcated from the road by a curb 0.10 to 0.15 m (4 to 6 in.) high. The traffic load was higher at KV than at RV, but vehicle speed, especially by buses, appeared higher at RV.

At RV, three groups of trees were included. Two types of straw mat configurations were tested against a control without protection. One protective measure was a box or square around the tree. The dimensions of the square were approximately 3 × 3 m (10 × 10 ft). The other protective measure was a skirt around the tree trunk. The height of the skirt was 1.2 m (4 ft). At the soil surface, the diameter of the skirt was approximately 1.0 m (3.3 ft). At the top, the skirt was wound tightly around the trunk, but stem flow was not prevented.

The trees at KV were generally unhealthy, suffering from premature autumn coloring and twig and limb dieback, and most trees showed a characteristic witch's broom structure. At this site, three types of straw mat configurations were compared to a control (Figure 1). Besides the box or square and the skirt protective measures, an arrangement of parallel straw mats (parallels) was included. Except for the mats transversing the strip (connecting the mats run-

Table 1. Tree and site characteristics at Ravnsnæsvej road (RV) and Kongevejen road (KV).

Tree/site characteristic	RV	KV
Species	*Acer plataniodes*	*Quercus robur*
Year of planting	1991	1984
Height (m)	6.7	3.5–7.5
Diameter at breast height (cm)	7.9	6–15.5
Health status (visual inspection)	Healthy, few chloroses	Many necroses and chloroses
Width of median strip (m)	6	3.8
Planting distance from roadside (m)	On a line, 1.9 m from one side	In the middle, 1.9 m from both sides
Number of trees	3 × 3 trees	4 trees
Distance between trees (m)	10 m between trees in the groups; 25 m between groups	10 m between trees
Width of carriageway (m)	2 × 5	2 × 7
Lanes on the carriageway	1 in each direction	2 in each direction
Traffic load (cars per day)	24,600	7,000
Applied deicer, mean of 1997–1998 and 1998–1999 (kg/m^2)	1.1	1.1

ning parallel along the roadsides), this setup was identical to that of the square. All sides of the square as well as of the parallel were 3.8 m (12.5 ft) long. The skirt had the same dimensions as on RV.

At both sites, the straw mats were lined with plastic. On the mats facing the road, the plastic protruded from the lower edge of the mats to ensure draining directly to the road. According to local authorities, the height of the mats was allowed to be only 0.55 m (1.8 ft) to prevent blocking the views of vehicle drivers. The protective mats were mounted on 15 November prior to salting and taken down on 15 April after salting was concluded for the season.

Measurements and Laboratory Methods

Salt deposition to the median strips was estimated by means of 0.3-m high (1 ft) funnels connected to buried receptacles. Stem flow was collected by means of a girdle twisted around the tree trunks covered by skirts. The flow water was stored in buried receptacles. The flow down the straw skirt was measured by means of 0.15-m wide (6 in.), specially designed funnels.

Soil water was collected by means of continuous suction through Teflon soil water samplers (Prenart Equipment) placed approximately 0.4 m (1.3 ft) deep. Both funnels and soil water samplers were connected to buried receptacles to keep the collected water as cold as possible and away from the sunlight.

At RV, the effect of the distance from the road was quantified at one side of the median strip by means of instruments placed 0.6, 1.55, 2.55, and 3.55 m (2, 5, 8.4, and 11.6 ft) from the roadside. At the other side, instruments were placed 0.6 and 1.9 m (2 and 6.2 ft) from the roadside at each protective measure. At KV, the same instrumentation was kept on both sides of the median strip. Instruments were placed 0.6, 1.2, and 1.9 m (2, 4, and 6.2 ft) from each roadside. In the laboratory, sodium (Na) was determined on ICP (Perkin Elmer Optima 3000 XL) and chloride (Cl) was measured by ioncromotography (Shimadzu LC 10AD).

RESULTS AND DISCUSSION

Deposition

The effects of different protective measures on the inexpedient road salt deposition at the median strips are shown in Table 2. The deposition figures consist

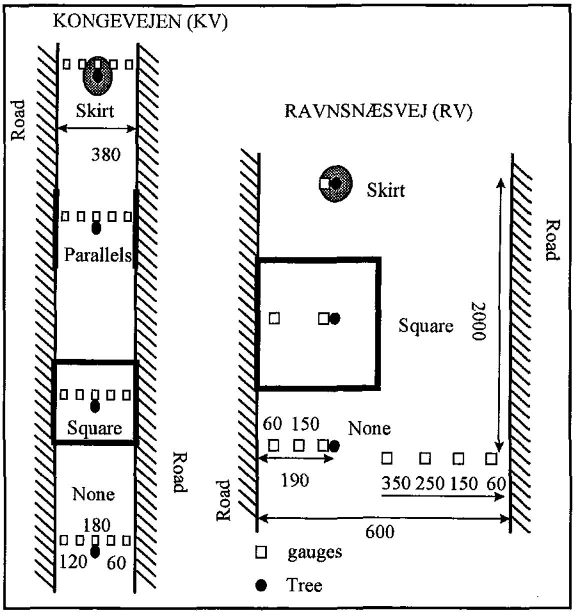

Figure 1. Experimental area at the median strips at Ravnsnæsvej (RV) and Kongevejen (KV), Copenhagen, Denmark. At RV, only one of the tree groups is shown.

of a sea salt and a road salt component. However, the sea salt was of minor importance, less than 8 g/m² (estimated on the basis of the salt concentration in the precipitation collected outside the period of road salt application). Also, the stem flow was of minor importance. In the two seasons, approximately 2 g/m² (as a mean) flowed down the stems.

Only the parallels and the squares resulted in a significantly decreased deposition at the central strips. Inside the squares, the decrease was very conspicuous all along the cross section of the central strip. However, the parallels resulted in only minor fluxes at the roadside and did not provide a substantially smaller deposition near the trees 1.9 m (6.2 ft.) from the roadside.

The skirt flux around the trees (distance of 1.9 m [6.2 ft]) was calculated as the total of two components: 1) the flux down the exterior side of the skirt, and 2) the flux to the area outside the skirt cover. This combined flux (Table 2) was nearly identical to the flux where no protection measure was mounted. Also, the fluxes at the other distances not protected by the skirt were almost equal to the fluxes without protective measures.

Table 2. NaCl deposition (g/m²) at median strips in relation to protective measures. Mean values (15 November 1997 to 15 April 1998, and 15 November 1998 to 15 April 1999). The relation between Na and Cl is almost constant, Na/Cl being approximately 0.59.

	KV Mat type				RV Mat type		
Road distance	None	Parallel	Square	Skirt	None	Square	Skirt
0.6 m	295	184	104	312	364	45	360
1.2/1.5[z] m	215	115	59	213	96	—	—
1.9[y] m	140	165	82	131	56	30	53

[z]KV 1.2 m, RV 1.5 m.
[y]At the trees.

In general, square-shaped straw mat arrangements seemed to be the only tested protective measure that actually reduced the load of soil NaCl significantly at the planting sites in the median strips. Without doubt, the lined skirts impeded the salt fluxes inside the mats, but the fluxes down the exterior sides were increased accordingly. Because the skirts had a smaller diameter (only 1 m [3.3 ft]), the salt load on the area above the main part of the root system was probably similar to the load found on the areas without protection.

At both sites, increasing the roadside distance from 0.6 to 1.9 m (2 to 6.2 ft) where no protective treatments were mounted resulted in a significant decreased deposition (50% to 80%). By introducing the square protective measures close to the roadside, it seems possible to improve the reduction up to 70% to 90%.

The salt deposition in the two years was comparable in magnitude, although the distribution varied with the largest amount deposited in February 1997 and 1998 and in March 1998 and 1999. Figure 2 illustrates the average yearly deposition at RV at different roadside distances. The mean deposition in the two years was 441 g/m² at 0.6 m (2 ft), 96 g/m² at 1.5 m (5 ft), 46 g/m² at 2.5 m (8.2 ft), and 51 g/m² at 3.5 m (11.5 ft). Beyond 2 m (6.6 ft), no significant change in the salt load could be observed. The slightly larger deposition at 3.5 m compared to that at 2.5 m could probably be explained by additional deposition from the opposite roadside (distance approximately 2.5 m). The largest deposition definitely occurred close to the roadside and seemed to decline exponentially toward the middle of the median strip.

The salt applications to the experiment roads RV and KV are presented in Table 1. In total, 1.8 kg NaCl per linear meter of this application was deposited at the wide median strip at RV without protective measures, corresponding to 0.3 kg NaCl per m² as a mean. At the narrower median strip at KV, total deposition was estimated at 1.6 kg NaCl per linear meter and 0.8 kg NaCl per m² as a mean. The square at RV reduced the total salt deposition to the median strip by 70% but the deposition near the trees in the middle of the strip by only 44% (Table 2). Similarly, the square at KV reduced the total salt deposition and the deposition close to the trees by approximately 80% and 40%, respectively. The reduction at the parallels was 60% of the total deposition. An increase of 15% was observed close to the trees.

Because traffic occurs on both sides of the median strip, it is assumed that the roadsides and median strips received road salt from both separate carriageways, and approximately 20% to 30% of the applied deicers ended up at the median strip. These portions were reduced by the square and parallel mats to approximately 5% and 9%, respectively.

The load of road salt to the median strips was reduced considerably by the square mats. However,

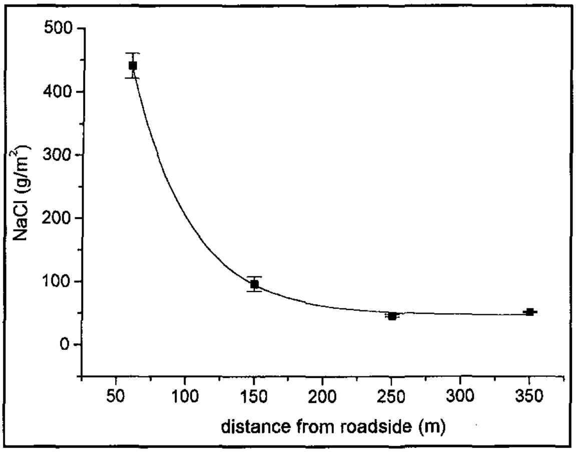

Figure 2. Deposition of road salt (NaCl) at different roadside distances at the median strip at RV. Error bars are calculated as standard errors (n = 3). The presented curve is the best first-order exponential fit.

increasing the distances of the trees from the roadside beyond approximately 2 m (6.6 ft.) seemed to have the most notable influence on reducing deicing salt deposition on trees and the soil.

Soil Water Concentrations

During the study period, soil water salt concentrations were high, between 20 and 100 times as high as under forest conditions in Denmark (Pedersen 1993; Pedersen and Bille-Hansen 1995). Even though the concentrations peaked in the salt application period during winter dormancy (Figure 3 and Figure 4), the concentrations remained high during the period of growth (Table 3). Despite abundant precipitation (200 to 300 mm [7.9 to 11.8 in.]), there was a tendency to only insignificantly decrease concentrations during spring followed by increasing concentrations during the summer and a pronounced decrease in the late autumn.

The salt leaching in spring was not complete. No leaching occurred during the summer period; instead, the salt in the soil water became concentrated as a result of evapotranspiration. Most of the NaCl was not leached until the rainy autumn; the soil water then reached concentration levels of about 100 mg/L.

The protective measures apparently resulted in 10% to 50% lower salt concentrations in the growth period at KV (Table 3). The smallest reductions were observed close to the roadside. The most pronounced reduction occurred in connection with the square. At RV, no effects of the protective measures on the trees were observed at 1.9 m (6.2 ft)

NaCl concentrations in the soil water mirrored the deposition figures. Very high concentrations occurred close to roadside. The average NaCl concentrations for the whole study period were 1,595 mg/L at 0.6 m (2 ft), 384 mg/L at 1.5 m (5 ft), 248 mg/L at 2.5 m (8.2 ft), and 235 mg/L at 3.5 m (11.5 ft) from the roadside. As with deposition, the soil water concentrations seemed to decline exponentially toward the middle of the median strip, with only insignificant changes beyond 2 m (6.6 ft).

The effect of the protective measures on the soil water concentration of road salt was limited. However, increasing the distances from the roadside clearly diminished the potential for stress by soil salt but rarely reduced the concentrations to levels normally regarded as acceptable for root growth.

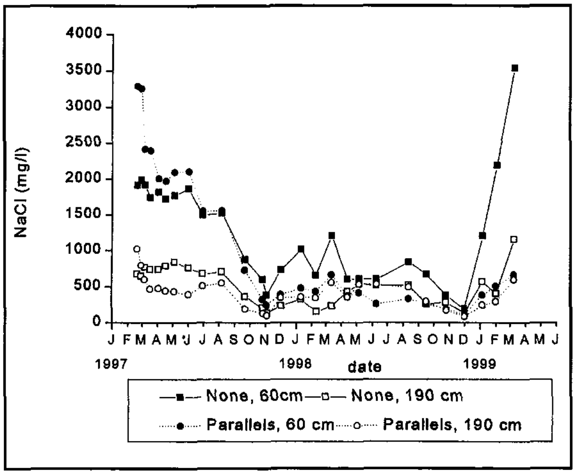

Figure 3. Concentration of NaCl in the soil water at the median strip at KV. Concentraions are given for distances of 60 an 190 cm (24 and 75 in.) from the roadside without protective measures as well as with a protection measure of parallel straw mats.

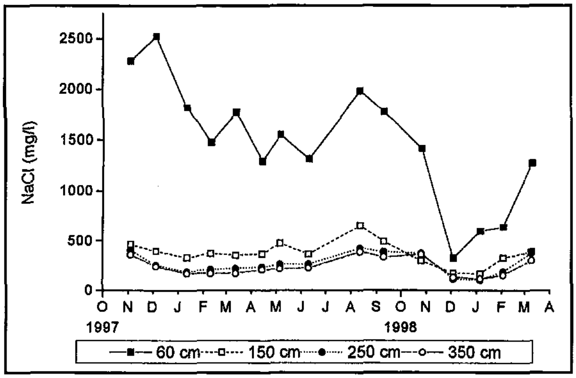

Figure 4. Concentration of NaCl in the soil water at different distances at RV (without protective measures).

CONCLUSIONS

This study indicates that damages from road salt are strongly affected by road distance. Variation in soil salt concentrations within the year was highlighted, and the existence of elevated salt concentrations in the soil water during the growth period was documented.

From this study, it is evident that the tested straw mats protect only if they are placed on all sides of the tree. Neither skirt protective mats around the stem nor parallel protective mats along the roadside

Table 3. NaCl concentrations in the soil water (mg NaCl per L) at the median strips in relation to protection measures. Mean values during the period of growth (May through September). The relation between Na and Cl is almost constant, Na/Cl being approximately 0.59.

	KV Mat type				RV Mat type		
Road distance	None	Parallel	Square	Skirt	None	Square	Skirt
0.6 m	1,135	1,031	718	983	1,588	823	—
1.2/1.5[z] m	928	703	327	852	460	—	—
1.9[y] m	572	432	302	405	324	321	326

[z]KV 1.2 m, RV 1.5 m.
[y]At the trees.

seemed to provide adequate protection. Skirts around the stems did not provide any protection. At distances of approximately 2.0 m (6.6 ft.) or more from the roadsides, only small protective effects were found among treatments.

Our results suggest that we tailor our use of straw mat protective measures. Increasing the planting distance from the roadside has a dramatic effect on the reduction of the potential salt stress. If possible, it is preferable to plant at least 2 m (6.6 ft.) from the roadsides. Only when the load of road salt is very high should significant effects of protective measures be expected. In situations with lower distances to the roadside, the type of protective measure used should be considered carefully. In planted median strips the square-type protection is recommended.

Parallels may be useful in some situations in median strips but did not show convincing effects in terms of reducing salt deposition and salt concentrations in the soil water. Skirts cannot be recommended in median strips. This type of protection should be restricted to paved areas where the skirt outside discharges directly to the road surface.

Stem flow did not alter the deicing salt concentration in the soil water. Leaching of deicing salt in early spring is insufficient to significantly reduce the NaCl concentrations in the soil water. Over a two-year period, high levels of NaCl were observed all year round, with lowest levels in November and December. The amount of leaching was dependent on annual rainfall.

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Acknowledgements. We are grateful for the financial support for this investigation from the counties of Copenhagen and Frederiksborg. Also, we wish to thank Mogens Poulsen and Søren Glusted at the two counties for providing valuable feedback during the whole project period. The authors also wish to thank the staff at the laboratory at The Danish Forest and Landscape Institute, especially Andreas Harder for his excellent field work in a stressful environment.

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Zusammenfassung. In Kopenhagen, Dänemark, wurden die Ablagerungsmuster von Streusalz und die daraus resultierenden Konzentrationen im Boden im bepflanzten Mittelstreifen von zwei Strassen bestimmt. Die Hauptziele bestanden darin, den Einfluß der Distanz zur Strassenseite zu bewerten und verschiedene Schutzeinrichtungen aus Strohmatten zu testen. Die Deposition und die die Bodenwasserkonzentration von NaCl sank deutlich auf den ersten paar Metern Abstand im Vergleich zu weiter entfernten Flächen. Wenn die Strohmatten wie ein Rock um die Stammbasis gelegt wurde, stellte es keinen ordentlichen Schutz gegen Streusalzdrift und hohe Konzentration im Bodnewasser dar. Im Gegensatz dazu stellte sich bei der Bedeckung mit Strohmatten auf allen Flächen der Baumweite ein kleiner, aber messbarer Effekt ein. Die höchste NaCl-Konzentration im Bodenwasser wurde während des Winters beobachtet. Trotzdem bestand eine starke Tendenz zu einer anhaltenden Konzentrationsstärke während des nachfolgenden Sommers. Das bedeutet, daß es einen ernsten Salzstress während der Wachstumsperiode gibt. Daraus ist zu schließen, daß ein Pflanzabstand von mehr als zwei Metern von der Strasse die unerwünschten Effekte des Streusalzes auf Bäume reduziert und auch die Salzkonzentration im Bodenwasser geringer ist als bei der Anwendung von Strohmatten.

Résumé. Le modèle de déposition du sel de déglaçage ainsi que les concentrations résultantes dans le sol a été établi sur deux terre-plein de route avec des végétaux à Copenhague au Danemark. Les objectifs premiers sont d'évaluer l'effet de la distance par rapport au bord de la route et de tester différentes mesures de protection faites de matelas de paille. Le dépôt et les concentrations de NaCl dans l'eau décroissent significativement à l'intérieur des premiers mètres depuis le bord de la route comparativement aux zones au-delà de cette distance. Les matelas de paille installés sous la forme de jupes autour des troncs des arbres ne se sont pas avérés être une protection efficace contre les embruns de sel et les concentrations élevées de sel dans l'eau. Par contre, la protection avec des matelas de paille sur tous les côtés de la largeur de l'arbre a donné un petit effet, mais mesurable. Les plus fortes concentrations de NaCl dans l'eau du sol ont été mesurées durant l'hiver. Néanmoins, il y avait une très forte tendance vers une persistance de concentrations élevées tout au long de la saison estivale suivante. Ceci suggère qu'il existe un stress salin sévère pour les arbres durant la saison de croissance. On peut en conclure que planter à une distance de plus de 2 m du bord de la route permet de réduire les effets indésirables des dépôts d'embruns salés sur les arbres tout comme celui des concentration de sel dans l'eau du sol, et ce plus efficacement que l'emploi de matelas de paille.

Resumen. Se determinó el patrón de deposición de las sales por deshielo y las concentraciones resultantes en el suelo, en fajas de plantación de árboles en dos carreteras en Copenhagen, Dinamarca. Los principales propósitos fueron evaluar el efecto de las distancias a los bordes de las carreteras y probar diferentes medidas de protección hechas con esteras de paja. La deposición y concentraciones en el agua del suelo de NaCl disminuyeron significativamente dentro de los primeros metros del borde de la carretera, comparado con áreas lejos de allí. Las esteras de paja montadas como falda alrededor del tronco del árbol no constituyeron una protección apropiada contra la espuma de sal y sus altas concentraciones en el agua del suelo.. En contraste, la protección con esteras de paja en todos los lados alrededor del árbol resultó en un pequeño pero mensurable efecto. Las concentraciones más altas de NaCl en el agua del suelo se vieron durante el invierno. Sin embargo, hubo una fuerte tendencia de elevadas concentraciones persistente a través del verano subsecuente. Esto sugiere un serio estrés por sales sobre los árboles durante la estación de crecimiento. Se concluye que la plantación a una distancia de más de 2 m del borde de la carretera reduce más eficientemente los efectos indeseables sobre los árboles de la deposición de espuma de sales como también de la concentración de sales en el agua del suelo, que el uso de esteras de paja.