De-icing salt and the roadside environment

Göran Blomqvist, 2001

Preface

This thesis is a result of four and a half years of studies performed at the Royal Institute of Technology (KTH) in Stockholm. The project ”Influence of De-icing salt on Roadside Vegetation” (VTI Project No 80131) has been financed by the Swedish National Road Administration (SNRA) through the Centre for Research and Education in Operation and Maintenance of Infrastructure (CDU). During the project, I have been employed by the Swedish National Road and Transport Research Institute (VTI) in Linköping. This mixture of having two ”homes”, one at the division of Land and Water Resources at KTH and one at the division of Road Maintenance and Operations at VTI has helped me in my intention of finding a perspective to the issue that can appeal both the applied sense of the clients (SNRA and CDU) and the requirements for the PhD dissertation.

The study is related to several fields of science. Therefore I have constructed a glossary for the dissertation text, where some important words are explained. The glossary can be found before the references.

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List of papers

The thesis is based on the following papers which are referred to in the text by their respective Roman numerals.

Paper I

Blomqvist, G. (2001), Long-Term Effects of Deicing Salt on the Roadside Environment. Part I: Forestry, *Transportation Research Board Conference Proceedings* **23**:179–185.

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Paper II

Blomqvist G. and Johansson E.-L. (1999), Airborne spreading and deposition of de-icing salt – a case study, *The Science of the Total Environment* **235**:161–168.

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Paper III

Blomqvist, G. Patterns of chloride deposition next to a road as influenced by salting occasions and winds, **Manuscript.**

Paper IV

Blomqvist, G. The response of Norway spruce seedlings to roadside exposure of de-icing salt, **Manuscript**.

Paper V

Blomqvist, G. and Folkeson, L. Indicators for monitoring the system of de-icing salt use and its impacts on groundwater, vegetation and societal assets, **Manuscript.**

Background

The environmental impact of winter road maintenance on vegetation has been studied for about three decades in Sweden (Segerros, 1972; Rühling, 1974; Bäckman et al., 1979). However, during the mid 1990s, damage was observed to vegetation along heavily trafficked roads in southern Sweden to an extent that had not been seen earlier (Bäckman & Folkeson, 1995). This highlighted the need for more explicit studies of the relationship between winter maintenance and vegetation damage and therefore the project ”Influence of De-icing salt on Roadside Vegetation” was started. The project resulted in a licentiate thesis ”Air-borne transport of de-icing salt and damage to pine and spruce trees in a roadside environment” (Blomqvist, 1999) which pointed out some objectives for the future studies on which the present doctoral thesis is based.

Introduction

In June 1998, the Swedish Parliament adopted a new transport policy on the basis of the Government Bill “Transport policy for sustainable development” (1997). The overall goal of the transport policy is defined to be a transport system that is environmentally, economically, culturally, and socially sustainable. The overall goal was divided into five sub-goals: an accessible transport system, a high transport quality, a safe traffic, a good environment, and a positive regional development. In addition to that, the Swedish Roads Act (1971, section 23) states that roads shall be held in a satisfactory state by maintenance and other measures. Therefore, in order to maintain road safety and accessibility of the road network at acceptable levels also during the winter season, the roads are kept free from ice and snow by ploughing and by the use of chemical de-icing. The winter road maintenance regulations of Sweden (Drift 96…, 1996) prescribe sodium chloride as the only allowed chemical de-icing agent to be used. Unfortunately the salt solution does not stay on the road surface where its effects are desired, but will by different mechanisms be dispersed into the roadside where it may lead to undesired environmental impacts (Blomqvist, 1999; Thunqvist, 2000). The question of whether the goals of accessibility, transport quality and safety can be fulfilled at the same time as the goal of a good environment is fulfilled, must therefore be seen as a delicate matter of conflicting interests.

The system of de-icing action and its consequences, both desired and undesired, has been studied more or less since the use of salt in winter maintenance started in America in the 1930’s (D’Itri, 1992). From that time and on, the amount of salt used has increased following the development of motoring. Many of the studies concerning the environmental impacts of salt have been dealing with either vegetation, soil, groundwater or surface waters.

The Swedish National Road Administration (SNRA) is responsible for the winter road maintenance of about 98 000 km of state roads in Sweden (Ölander, 2000). The de-iced roads are divided into three classes depending on the annual average daily traffic (AADT) and each class is described by a level of service giving its priority in being treated and the minimal appropriate treatment (Drift 96…, 1996; Holldorb, 2000). Twenty-five per cent of the SNRA appropriation for road maintenance and operations is spent on winter road maintenance works, such as snow ploughing and de-icing (Ölander, 2000). The de-icing salt use on the national road network has approximately doubled since the 1970's and has for the last six seasons varied in the size between 200 000 and 300 000 metric tonnes (figure 1).

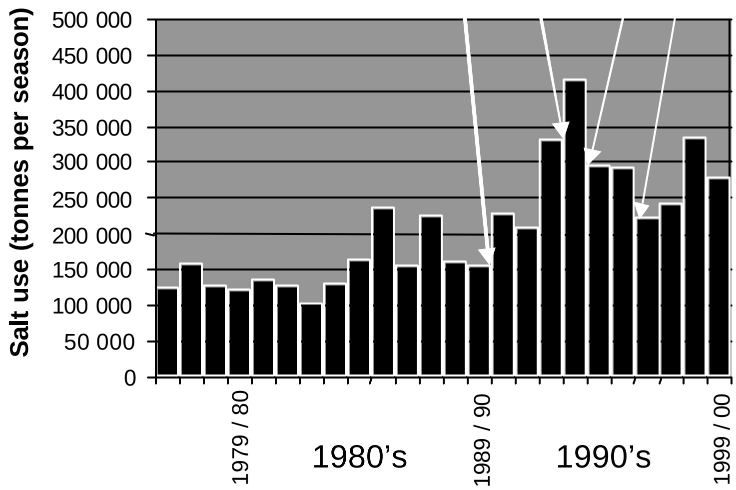

Figure 1 *The seasonal salt use on the Swedish national road network (metric tonnes per season). The arrows depict the changes in the winter road maintenance regulations during the last decade. Before that the winter maintenance was regulated in five-year plans.*

The winter road maintenance regulations have changed several times during the last decade (figure 1). The SNRA has a constant ambition of improving the requirements. In 1996 a limit value of 200 000 tonnes salt per year was set up as a goal to be reached by the year 2000 (Kretsloppsanpassad väghållning… 1996). This goal was indeed reached as the salt-use in the calendar year of 2000 was 196 700 tonnes (Pettersson, personal communication). For the future, the strategy for decreasing the salt use is the development of a salt index that allows the actual salt use to be compared to the salt needed according to the weather conditions prevailing during the entire winter (Ölander, personal communication). In that way the actions of the contractors can be compared to the requirements of the regulations.

A key issue when taking management decisions in the road sector is to ensure that limited funds are spent to greatest effect within the various constraints that pertain (Robinson et al., 1998). Knowledge of the different interrelationships within the system is therefore of great importance. Since 1999 the Swedish Environmental Code (1998, chapter 2, section 2) states that those who pursue an activity or take a measure, or intend to do so, must possess the knowledge that is necessary in view of the nature and scope of the activity or measure to protect human health and the environment against damage or detriment.

Modelling the system

Full understanding of the total system is probably not possible, however, but by simplifying the system of the real world into a model to start with, a conceptual understanding of the total system could be reached. In order to grasp phenomena in the real world so that they can be followed up and evaluated, they have to be described in a way that allows them to be scientifically studied. The system of interest is simplified into a model by making a set of assumptions about how it works. Systems analysis aims to assist in finding ameliorative responses to problems through designing and evaluating programmes, decisions, and actions (Quade and Miser, 1985).

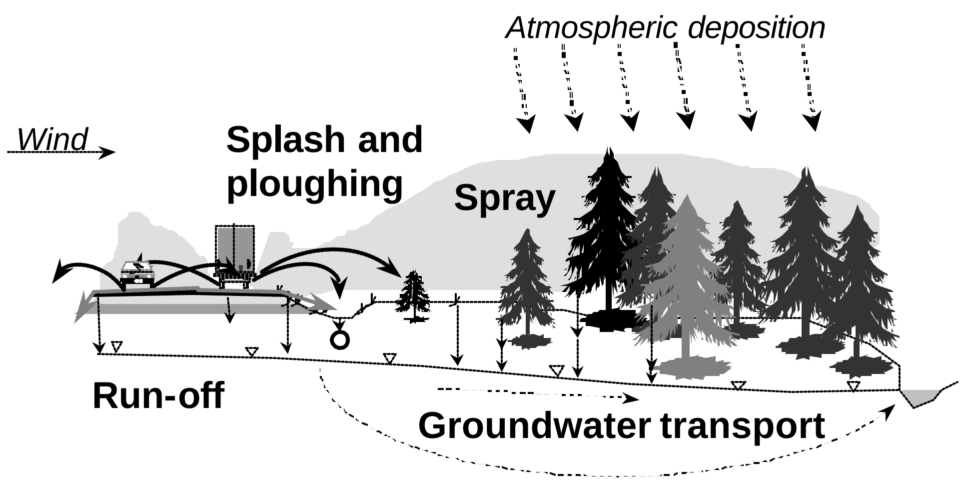

Figure 2 *A conceptual model of the transport mechanisms and pathways from the road.*

Compartment models

The system of de-icing salt can be described in several ways. This can be illustrated as in the picture above (figure 2) showing the transport mechanisms and pathways from the road, or as a box model divided into several compartments as shown below (figure 3). The de-icing salt is either transported through the compartments or accumulated within them.

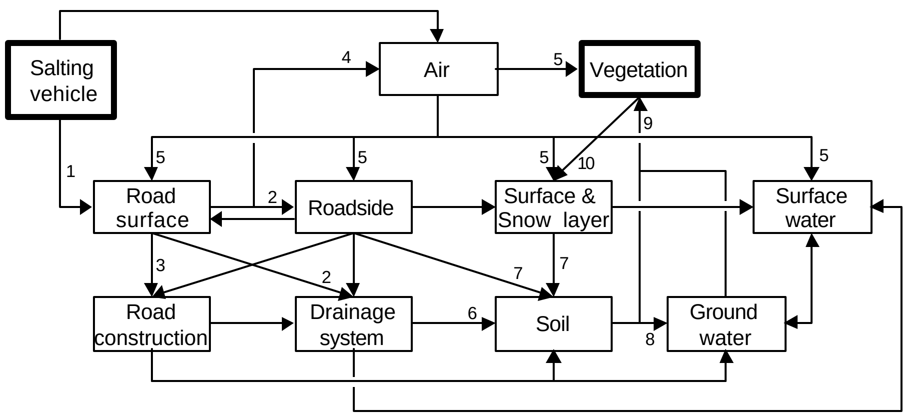

Figure 3 *A box model of the physical system of de-icing salt migration from the vehicle that carries on the de-icing actions to the compartments on, in or around the road which are involved in the migration or accumulation of de-icing salt. The boxes depict the compartments where the de-icing salt either is passing through or – to some extent – is retained or accumulated. The arrows depict the mechanisms that govern the migration of the de-icing salt, such as: deposition, runoff, infiltration, percolation, and root uptake.*

The de-icing vehicle applies the salt on to the road surface[1]. This is the action where the entire system origins. The salt will then leave the road surface by itself (by gravity) or by the action from traffic in the following ways. By run-off,[2] the salt will reach the roadside or the drainage systems. Some parts may infiltrate[3] the road surface and reach the interior of the road construction. By being forced into the air[4] by the vehicles or by ploughing, the salt leaves the road as splash, spray or dry crystals to be deposited[5] onto the road surface or roadside (roadside cover, ditch, etc.) of the technosphere or on the vegetation, soil surface, snow layer or surface waters in the surrounding ecosphere. By leaving the drainage system[6] or percolating[7] from the roadside or soil surface through the soil the salt soultion may reach the groundwater[8]. Where the soil solution and groundwater are in contact with the root zone of vegetation, uptake[9] through the roots may occur. Some part of the salt deposited onto the foliage, stem and branches of the vegetation will enter the interior of the plant, but a large portion will be transported as throughfall[10] and stemflow[10] to the soil surface beneath the vegetation.

The pathways by which the de-icing salt may reach the different plant parts have been discussed extensively in the literature. There is no doubt that damage may occur both when the salt is deposited onto the foliage and when it reaches the root system. This has been shown both in field studies and in laboratory studies under controlled conditions. When the salt is deposited on to the foliage it may either stay on the exterior parts (needles, leaves, stem etc.) or be transported to the interior of the plants either through the leaf cuticle or through the bark on the branches or stem (figure 4). Also the stomata have been suggested to be a pathway to the interior parts (Burkhardt and Eiden, 1994). Particles deposited on the exterior parts have been suggested to lead to damage (Flückiger et al. 1977).

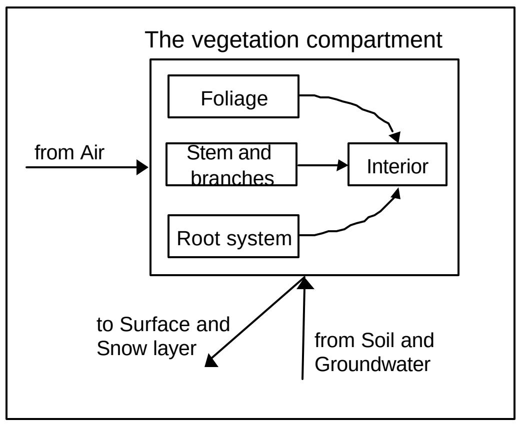

Figure 4 *The vegetation compartment in figure 3 can be subdivided into foliage, stem and branches, root system and the interior of plants.*

The salt that has percolated through the road construction, or roadside and reached the soil or groundwater will to a large extent be transported with the groundwater to the surface waters and then follow the water cycle to the sea. In that sense this is – in a very long time-scale – a geochemical cycle of salt, extracted from the seas or rocks, placed on the roads and then returning to the seas again. On the road surface, most effects are desired and in the seas salt is at least not harmful. The important issue is what happens in between (Thunqvist, 2000).

Monitoring the system

Robinson et al. (1998) have stated that: "A key challenge for the road manager is to find ways in which to describe the problems and impacts of road maintenance that can be understood by the politicians and the general public". One could also state that a crucial challenge for the scientific community would be to find key parameters and indicators of the system's different compartments that can be understood and utilised by the road managers (Paper I and V). A system that is used by the European Environmental Agency (EEA) as a generic tool to support understanding of complex environmental systems is the DPSIR model (Towards a transport and environment reporting mechanism 'TERM' for the EU, 1999). This system is used for facilitating communication and is based on indicators of the different compartments. Societal needs and activities can be viewed as driving forces (D) that lead to a pressure (P) on the environment. The pressure may change the state (S) of some compartments of the environment. This, in turn, can lead to impacts (I) on a system such as human health or nature. Finally, the society will respond (R) in some way to combat the problem in one or several of the earlier stages in the model (Figure 5). The DPSIR model is also chosen by the Swedish Environmenal Protection Agency for the follow-up of the 15 national environmental quality objectives (System med indikatorer…, 1999).

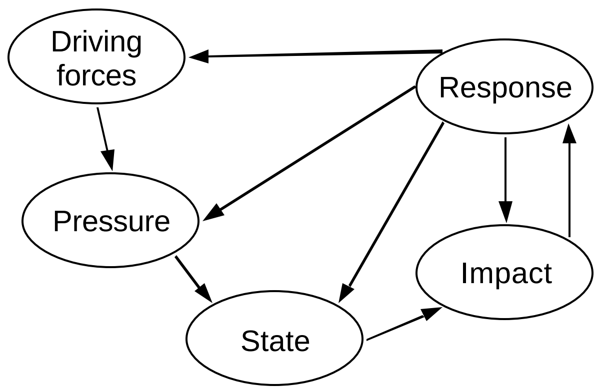

Figure 5 *The DPSIR framework for reporting on environmental issues*

Problem

After decades of investigations, we still have to deal with the problem of environmental effects of the use of de-icing salt in the winter road management. The regulations of the winter road management have changed four times during the 1990's (figure 1) but, since we don't have useful indicators of the environmental pressure, states and impacts, we still don't know the environmental utility of these changes.

Objectives

The objective of this thesis is to describe the system of de-icing practices and their environmental effects with special reference to the air-borne salt exposure of the roadside environment and damage to Norway spruce seedlings. The objective is also to propose a monitoring system of indicators that can be used for monitoring the driving forces, pressures, states, impacts and responses and thereby ultimately increase the knowledge of the environmental utility of the strategic actions taken by the road administrator.

Methods

The first paper describes the system of the use of de-icing salt and its impacts on roadside vegetation, especially regarding effects on roadside trees. The effects are described in the form of a DPSIR model where the impacts are grouped into three spheres of interest: the public, the landowners and ecology. The environmental acts, policies and strategies involved are referred to and to some extent discussed. *The second paper* is a case study where the air-borne spreading and deposition of de-icing salt is investigated at two field sites equipped with road weather information system installations. The deposition of salt collected in containers placed in transects perpendicular to the road is related to information of the wind characteristics from the road weather information system and salting data from the road administrators. *The third paper* describes the influence of wind and salting data in greater detail. *The fourth paper* describes the response of Norway spruce (*Picea abies* L. Karst.) seedlings to the exposure of de-icing salt and investigates the amount of damage in relation to the distance from the road, the concentration of chloride in needles in relation to the bulk deposition of chloride, and the extent of damage in relation to the concentration of chloride in needles. Also the influence of solar radiation for the mechanism of damage symptoms is discussed. *The fifth paper* discusses strategies for the follow-up of the system in relation to the Swedish environmental quality objectives and the environmental code and suggest improvements of the system for the follow-up of the environmental impacts on groundwater, vegetation and societal assets. Finally the most important indicators to be measured are suggested.

Summary of included papers

The effects of winter road maintenance constitute a complex system of many inter-relationships. One of these relationships is the effect of de-icing salt on vegetation. Using the DPSIR-model (figure 5), the use of de-icing salt and damage to vegetation could be described as follows. The need for transportation (D) leads to a roadside exposure to salt (P), which alters the state of the vegetation (S), thereby leading to different impacts (I), which may require some kind of response (R) from society (Figure 6, Paper I).

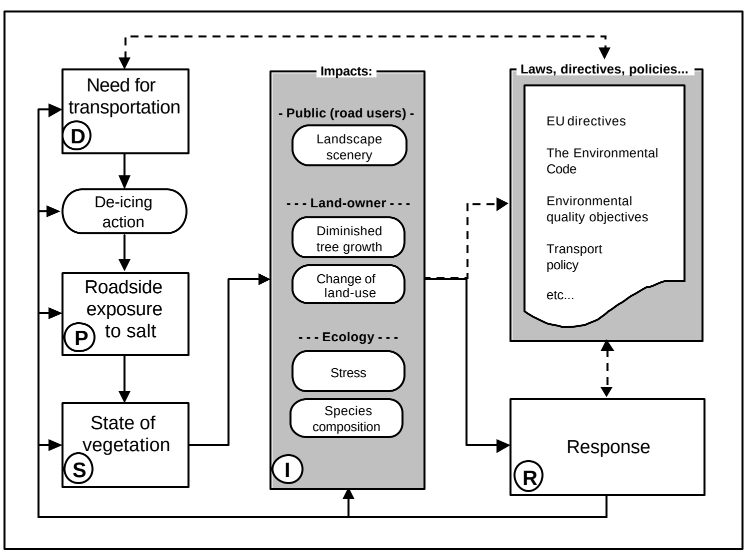

Figure 6 *The system of de-icing action and damage to vegetation as illustrated by the DPSIR model.*

The impacts have been divided into different spheres of interest where the interest of the public as road users is threatened by the impaired landscape scenery. The interest of the rural land-owners can be threatened by the diminished tree growth or the forced change of land-use that may occur if reforestation is made impossible in the salt exposed environment. The vegetation as part of the ecosystem can be influenced by being stressed and as a result there may be a change in the species composition of the roadsides.

By adding two new compartments to the original DPSIR model, the model is made suitable to be used for identifying the involved processes (Paper I). The two new compartments are the first oval between the driving force and pressure (figure 6) which represents the activity that is induced by the driving force, causing the pressure. In this case it is the actual de-icing measure taken. The other new compartment in figure 6 is the box of laws, directives, policies, regulations, contract conditions, etc. These are partly a result of the needs within the society (e.g. need for transportation is manifested in some of the goals of the transport policy), but it can also be used as a toolbox of the society to respond to all of the stages in the DPSIR model (Paper I).

In today's practice of winter operations in Sweden, the general recommendation is to "use as little salt as possible" (Paper I). It can be argued that this actually does not mirror an environmental concern, however. As long as the two words "as possible" are connected only to the requirements of a specific road surface friction value, or a tolerance limit of snow depth, within the regulations, there has not actually been any environmental consideration. As an alternative, the strategy for salting could be formulated as "use as much salt as possible". In this case the words "as possible" should instead be based on long-term tolerance limits of human health and nature, which is a basic concept in the government bill on which the current transport policy is based (Paper I).

The salt that is spread on the road surface will leave the road in different ways as influenced by different transport mechanisms. In paper II it is concluded that between 20 and 63 % of the de-icing salt applied on the road was transported by air and deposited on the ground 2–40 m from the road. Ninety percent or more of the total deposition within the profiles occurred within 20 m of the road. There seemed however to be some deposition also at longer distances than 40 m (Paper II). This could also be seen in Paper III (figure 7) where the deposition did not reach background values until a distance of some hundred meters.

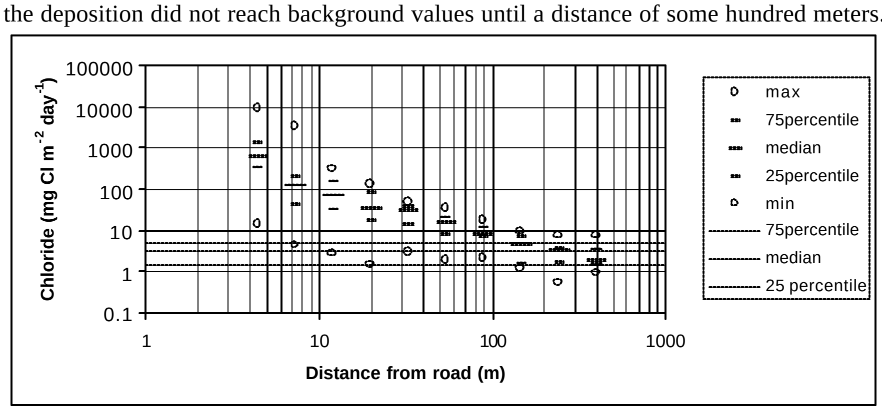

Figure 7 *Amount of chloride (mg Cl^{-2} day^{-1}) deposited in a profile perpendicular to the road, as compared to the background level (Paper III).*

The amount of salt used by the contractor on the road section showed good correlation to the amount of salt deposited in the roadside (Paper II and III, figure 8 and 9).

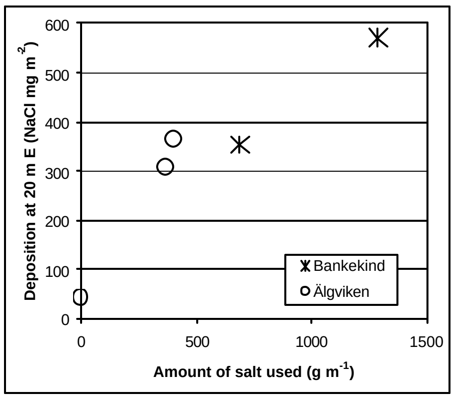

Figure 8 *The relation of salt-use and deposition of salt at 20 m distance (data from Paper II)*

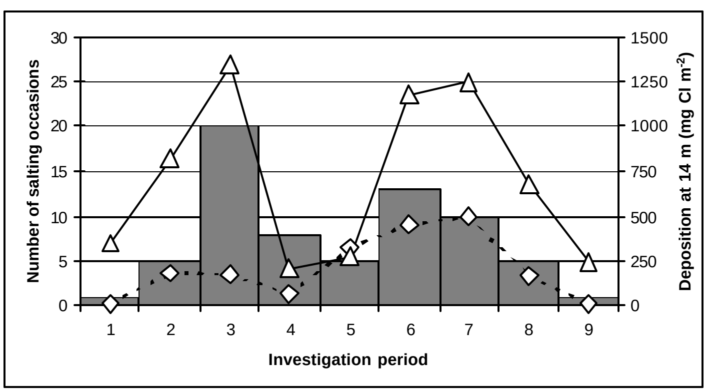

Figure 9 *The number of salting occasions (bars) as compared to deposition of salt at 14 m distance (Paper III). Triangles represent deposition on the southeastern side of the road, and squares represent the deposition on the northwestern side of the road.*

The deposition of salt showed to be different in the different sides of the road (Paper II, III, and figure 9). The amounts deposited were typically higher at one side of the road and in paper II it was concluded that the prevailing wind direction could be responsible for on which side of the road deposition was the highest. When the influence of winds was further investigated, it became evident that the wind direction played an important role as a factor influencing the mechanism of air-borne transport of the salt already at a distance of some ten metres from the road (Paper III, and figure 10)

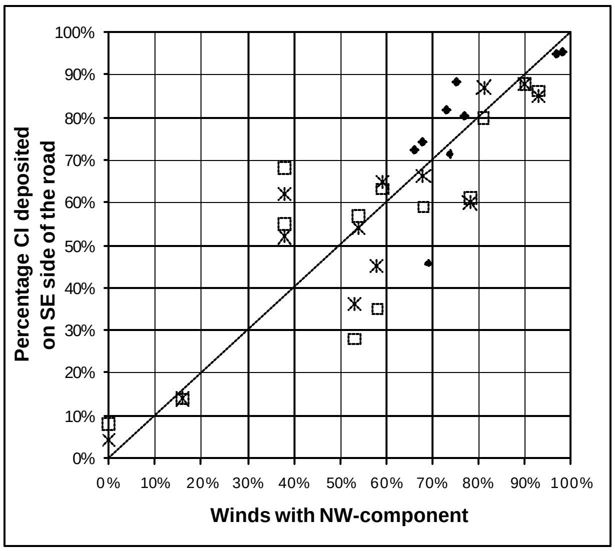

Figure 10 *Percentage of Cl deposited on the south-eastern side of the road as related to the percentage of winds with a NW-component. (? = 1998/99 12 m (n=13), * = 1998/99 20 m (n=13), ? = 2000 14 m (n=9).*

The wind speed showed a positive relationship to the distance to which the salt is transported (Paper III). The larger the sum of the wind component perpendicular to the road, the longer the distance where the deposition could be defined as raised in comparison to the deposition at the longest distance in the transect. From the results in paper II, it could be suggested that this relationship is not linear (figure 11).

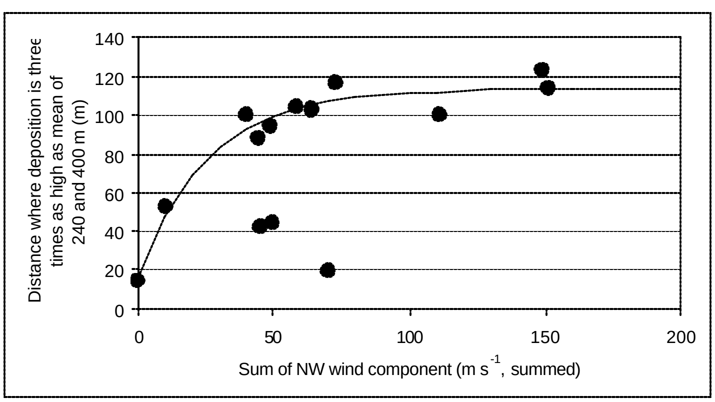

Figure 11 *The distance at which the amount of deposition of chloride was three times that measured at a distance well away from the road. The dashed curve is a hypothetic function describing the influence of the wind speed on the air-borne transport mechanism*

The suggested function of the variables distance and wind speed in figure 11 is of the form

$$\text{Distance} \; ? \; a(b \; ? \; e^{? c \cdot \text{wind}})$$

where a= 96.67, b=1.174 and c=0.039. The “Distance” denotes the distance at which the amount of deposition was three times higher than the mean deposition of 240 and 400 m. The “wind” is the sum of the NW wind component (perpendicular to the road). If this suggestion is true, which would need deeper investigation to be proven, it means that the wind speed is only influencing the deposition up to a certain distance, and at longer distances the wind speed is without importance for the deposition. One can, however, note that not all the data in the investigation fit to this suggested function (figure 11) and there can be many reasons for this. If there for instance would occur a rainfall event with high concentration of chloride, this would decrease the distance from the road where the chloride originating from the de-icing chemicals can be detected. More important in this investigation would be to be able to know when the de-icing action takes place and what the circumstances are at that time. Both weather characteristics, and traffic characteristics would probably be of importance. In order to reach a deeper understanding of this phenomenon, there is need to investigate the factors of wind and salting occasions more thoroughly.

To investigate the response on tree plants, seedlings of Norway spruce was used (Paper IV). The first investigation was a study of almost an entire winter season, where the exposure of the seedlings to air-borne de-icing salt was examined. The seedlings that were exposed at 12 m from the road were almost completely dead whereas the seedlings in the background locations were very healthy (Figure 12). By exposing another series of seedlings to only weekly exposure to the roadside conditions at 20 m distance from the road, it was found that the degree of damage was between 5 and 60 % dead needle tissue (figure 12). The degree of damage was established by visual classification of the ratio of brown and green needle tissue (Paper IV). The next winter (January–March 2000), the weekly exposure was repeated, but in order to reach a greater variation in the degree of exposure the distance of 20 m was supplemented by also using the distances of 14 and 30 m from the road. The response to the exposure was however very much lower than the year before (figure 12).

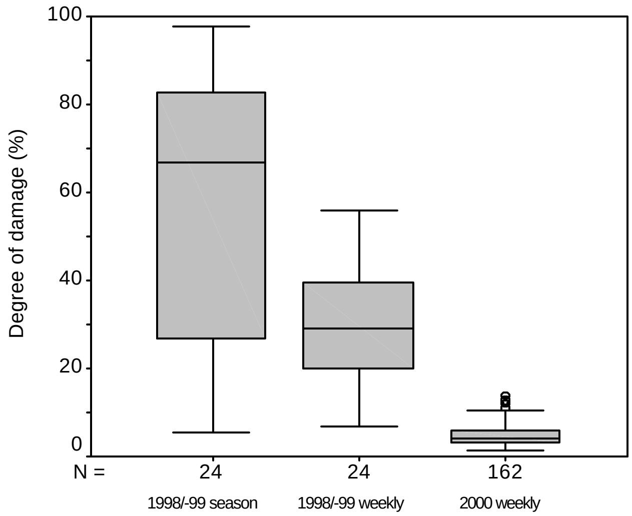

Figure 12 *A boxplot of the degree of damage in each damage study. The boxplot shows the minimum, 25-percentile, median, 75-percentile, and maximum value. In the 2000 weekly study the four highest values are considered to be outliers, since they exceed the distance of 1.5 boxlengths.*

The bulk deposition at each cassette for each week showed to be positively correlated to the chloride concentration of the unwashed needles after the season (Paper IV, and figure 13).

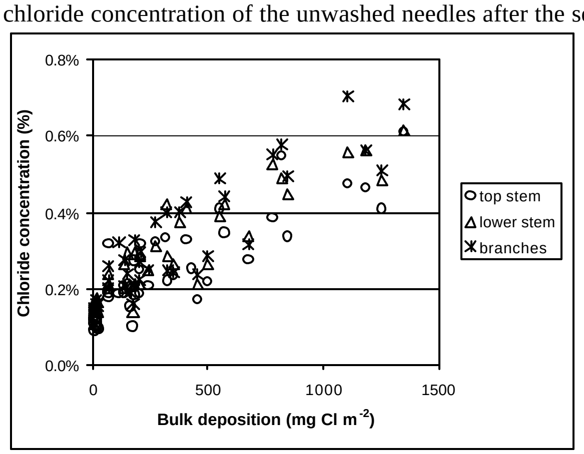

Figure 13 *Chloride concentration in needles as related to bulk deposition of chloride.*

Fitting a sigmoid curve to the data of the top stem portion of the seedlings exposed in the long-term investigation gave a fairly good fit (R^2=0.90, S=11.63). When treating the results of the three different investigations as one and the same population by fitting a curve to all data, the fit was still fairly good (R^2=0.89, S=6.24) (figure 14). It should be stressed though, that the three different investigations are indeed different and therefore should not be seen as one and the same population.

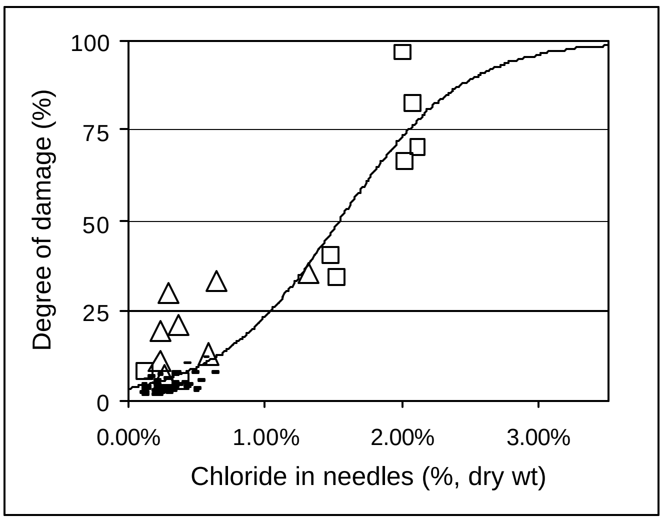

Figure 14 *A sigmoid curve fitted to all the data*

Fitting curves to data from the field can be difficult, since there are several reasons for deviations from the curve. The data may be shifted from the suggested sigmoid curve by the plants being more damaged than the salt concentration would suggest (data point shifted upwards). This could very well be the case since there are so many external factors influencing the total damage. Another way a point may be shifted is that the chloride concentration may be lower than the damage suggests. This can be an effect of the leaching of chloride from the damaged needles (Bedunah and Trlica, 1979).

There should be no doubt that the use of salt not only has desired impacts on traffic safety and road accessibility. As seen above (paper II and II) the de-icing salt will be transported into the roadsides and, as seen in paper IV, the roadside exposure to salt may lead do damage to vegetation. This damage can lead to different impacts depending on what interest is at stake (paper I). Therefore, and to fulfil the Environmental quality objectives and the requirements of the Environmental Code, the road-keeper needs to follow up the de-icing activities and their environmental impacts. A system of indicators for monitoring the various compartments of the system comprising the use of de-icing salt and its environmental impacts is suggested (paper V). The system is adapted to the DPSIR system which is widely used for environmental statistics in the European Union. The DPSIR system includes indicators for Driving forces that lead to a Pressure on the environment changing the State of compartments of the environment. The changes lead to various kinds of Impact. To combat the problems, society will Respond by taking various measures to improve the situation. The indicators are presented in table 1 (from paper V).

Table 1. *Suggested system of indicators (units in parantheses) for components of the system of de-icing salt use and its influence on water resources, vegetation and societal assets.*

	Water resources	Vegetation	Societal assets
Driving forces (D)	Traffic safety *(average annual daily traffic, AADT)*	Traffic safety *(AADT)*	Traffic safety *(AADT)*
Pressure (P)	Salt use *(mg Cl per litre)*	Salt exposure *(tonnes NaCl per km and winter)*	Salt exposure *(tonnes NaCl per km and winter)*
State (S)	Electric conductivity in water *(dS/m)* Salt concentration in water *(mg Cl per litre)*	Salt concentration in foliage *(% Cl in plant tissue, dry wt)*	Visual appearance *(km of road stretch with impaired scenery)*
Impacts (I)	Contamination of water supplies *(number of wells affected)*	Stress *(??)*	Impression *(number of registered complaints; letters to the press)*
Responses (R)	Salt-use restrictions *(salt index)* Protective installations *(number of installations, length of roads with gw protection)*	Salt-use restrictions *(salt index)* Spray-suppression systems *(number of installations, length of roads with spray protection)*	Removal of dead trees *(working time or cost spent)*

By using the structure of the DPSIR model, the structure of the system used today for follow-up can be improved (Paper V). There is however need for research in several areas related to this as for instance dealing with the involved processes of measuring salt transport, exposure and vulnerability, and about how the impacts should be valued. Even if these research needs are great in some aspects, there is still reason to take action by using the knowledge of today for the follow up, and improve the measures as knowledge increases by time.

Discussion

In the introduction, the long-term cycle of salt was discussed and it seems that the key issues appear when the activities and processes of the technosphere interfere with the natural conditions of the ecopshere (Figure 15). In simpler words, it is when the salt that is used on the roads leaves the road and exposes components that are either vulnerable to salt exposure or contain processes which, when disturbed by salt exposure, may lead to undesired secondary consequences, the environmental problems occur.

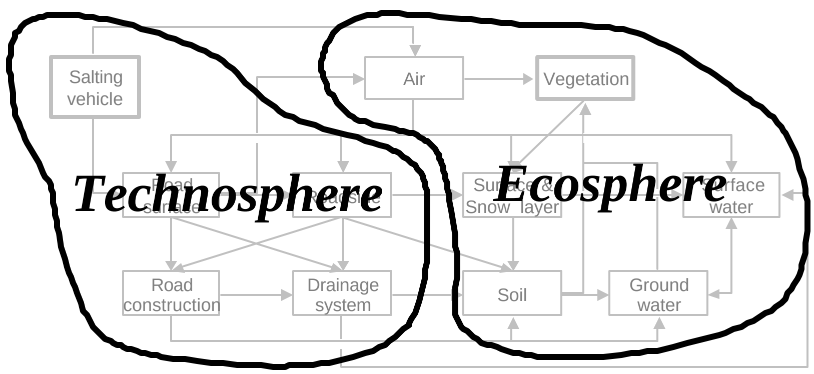

Figure 15 *The box model of the physical system of de-icing salt (figure 3) as divided into the technosphere which is strongly influenced by the human activity of de-icing and the ecophere, where the influence from de-icing is undesired.*

The ecosphere has a value in itself, seen from the ecocentric viewpoint, but should also be considered as an important resource for future use by mankind, as seen by the anthropocentric view.

One way to ameliorate the situation would be to cut off the salt pathway. Therefore the knowledge of the involved processes and the actual response of them is of importance. This requires tools for modelling and prediction of the processes involved, and tools for monitoring the resulting effects.

The DPSIR framework is useful in describing the relationships beween the origins and concequences of environmental problems, but in order to understand their dynamics it is also useful to focus on the **links** between the DPSIR elements (Smeets and Weterings, 1999) (figure 16). This requires more mechanistic models of the processes than what the causal chains of the DPSIR system itself will allow. The roadside exposure to salt is suggested to be a function of traffic characteristics (T), road surface characteristics (R), maintenance characteristics (M), weather characteristics (W), surrounding characteristics (S) and possibly something else (e). This could be described by the function:
Roadside Pressure = f (T, R, M, W, S, e).

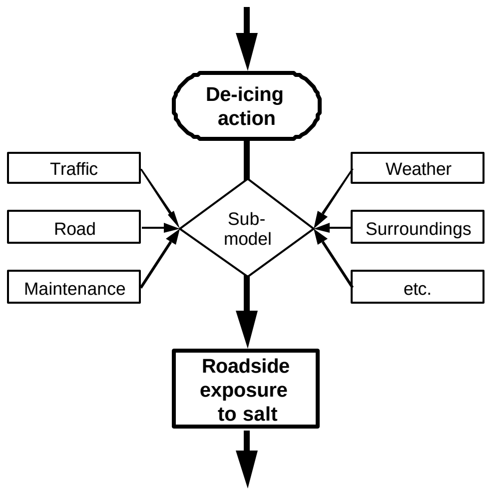

Figure 16 *The segment of the DPSIR model between the de-icing action following the driving force (D) and the roadside exposure to salt could be described by a submodel that is a function of the characteristics of the traffic, road, maintenance, meteorological factors and physical factors.*

In this study only the factors weather (wind direction and speed) and maintenance (amount of salt used) have been examined to some degree. The others remain to be elaborated, and in order to reach results that can be generalised into a manyfold of situations, there is need for a considerable research effort where the different characteristics of the factors described above are collected.

Blomqvist (1999) suggested the air borne spreading of salt to be described by a function of the added transport mechanisms of splash and spray, each of which was described by an exponential function. The total deposition at a certain distance was then suggested to be described by the function:

$$\text{Deposition} = a_{splash} \cdot e^{(b_{splash} \cdot \text{Distance})} + a_{spray} \cdot e^{(b_{spray} \cdot \text{Distance})} + \text{background}$$

The variables a_{splash}, b_{splash}, a_{spray} and b_{spray} are supposed to be related to the above mentioned five specific characteristics.

By fitting the suggested deposition function to the data from the present study it became apparent that the suggested function was not fit for describing the actual deposition pattern at all time periods (Figure 17). In the roadside area, however, the suggested function may still describe the deposition pattern. But at longer distances another mechanism, unknown to me so far, needs to be added. What specific circumstances that lead to this result is still unclear, however. One could suggest that it is some smaller portion of the aerosols carried by the wind but this remains to be investigated.

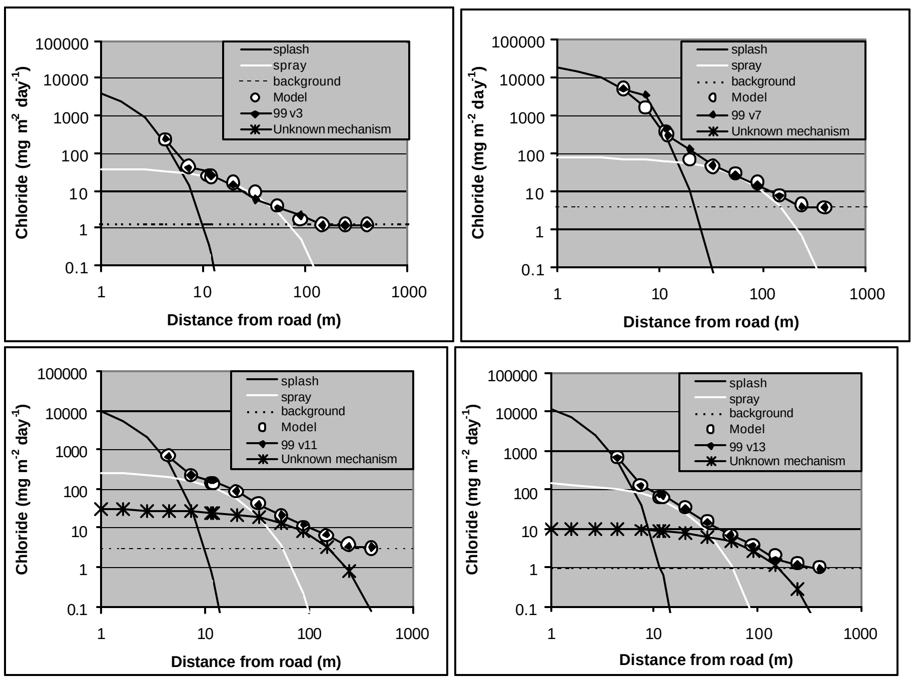

Figure 17 *Examples of different deposition pattern from the 1998/-99 investigation. Data from Paper III is used to test the model of added splash, spray and background mechanisms. In the two upper pictures (week three and seven) the described model(Blomqvist, 1999) is sufficient, but in the two lower pictures (week 11 and 13) yet another mechanism needs to be added.*

When considering the winds during the investigation of the deposition patterns (Paper III), the entire weeks have been aggregated since the exact time of the salting action was not known. The winds should, however, rather be weighted depending on the timing of the salting and the traffic amount at that time. When reconstructing the salt-use for one of the weeks by using the winds from the time when the salting vehicles left the garage and until six hours after they had returned there, it is seen that the wind situation is rather different (figure 18). Instead of 69 per cent northwesterly winds, the result is 50 per cent northwesterly winds, which is closer to what is supposed by the fact that 45 per cent of the deposition is found on the southeastern side of the road (Paper III).

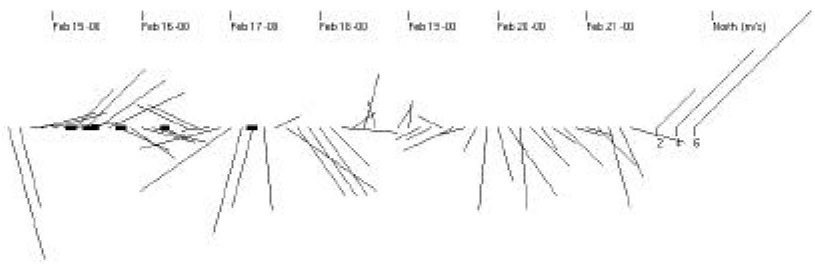

Figure 18 *A sea weed diagram of the winds during investigation week 5 in the year 2000 investigation of bulk deposition pattern. The thin lines are vectors representing the three hour wind measuresments (pointing in the downwind direction). In the far right end is a scale with the winds of 2, 4 and 6 m s^{-1} pointing towards a true north direction. The black boxes are the time range, when the salting action has taken place.*

When discussing the modelling of damage to vegetation, one must keep in mind that the concept of damage is quite complex as one environmental state often can be regarded from several perspectives, and hence the one and same state can impact different interests. De-icing salt induced damage to roadside vegetation in rural areas can for instance be divided into categories of impaired landscape scenery, diminished tree growth, forced change of land use, increased stress and changed species composition (Paper I). In built-up areas, damage to gardens may also be of importance.

The licentiate thesis "Air-borne transport of de-icing salt and damage to pine and spruce trees in a roadside environment" (Blomqvist, 1999), pointed out that the orientation of damage of conifers outside the splash-zone suggested an external factor aggravating the symptoms of de-icing salt damage. The contributing factor was suggested to be the solar radiation and the symptoms to be the same as for frost drought, although aggravated by the deposition of salt and mineral particles on the needles. Therefore a specific study based on the plant material presented in paper IV was designed in order to investigate the differences in the orientation of the damage symptoms. The ratio of damaged to non-damaged needle tissue was determined as explained in paper IV. In order to test in what direction the damage was largest the assumption that a sine-curve could be fit to the data was made. A mean value of the degree of damage to the top stem part of the seedlings was calculated for each direction (N, E, S, W). Then a sine-curve, $a + b \cdot \cos(direction)$, was fitted to the damage of each cassette by using the total mean as the constant *a* and half the damage range as the constant *b*. Shifting this curve sideways, by changing the variable *direction*, the most damaged direction was defined to be where the best fit was found. This resulted in a picture of the damage (figure 19) where the damaged cassettes on the southeastern side between 12 and 54 m were aligned around the western direction, while the cassettes on the northwestern side, and the cassette at 400 m southeast of the road instead were aligned around the south-southwestern direction. The reason for this could be that the combination of deposition pattern on the seedlings and the external factor of solar radiation both influence the mechanisms of damage. The experiment could not be reproduced in the consecutive season due to the very low degree of damage that year. Therefore the conclusions out of this experiment should not be drawn too far.

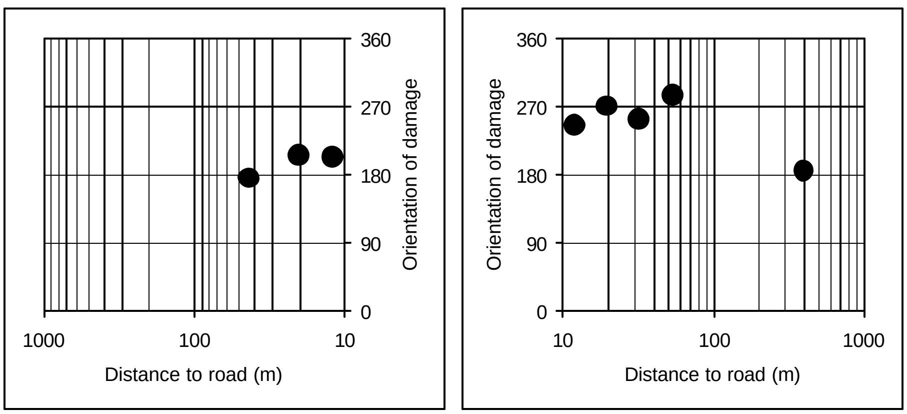

Figure 19 *The main orientation of damage to Norway spruce seedlings as compared to the distance from the road. Note that the left picture has a reversed scale on the x-axis. Left: northwestern side of the road. Right: southeastern side of the road.*

When assessing damage to Norway spruce trees and plants it is important to be able to differentiate between damage induced by salt and damage induced by other pathogenes (such as insects and fungi) or weather (frost and drought) or mechanical injuries. There are some fungi, commonly occurring in Sweden, which may cause symptoms that resemble those of salt damage. Among these are e.g. *Gremmeniella abietina*, Spruce needle rust (*Chrysomyxa abietis* and *Chrysomyxa ledii*) and Needle blight of spruce (*Lirula macrospora*). Each of these pathogens can be distiguished from the symptoms of de-icing salt damage. This demands, however, that the damage assessment is made at a certain timing when these differences are apparent.

It is also important to know that the different stress factors working in the roadside environment may either have predisposed the tree to damage, triggered the damage or contributed to the damage (Aronsson et al., 1995). Insects and fungi can both act as contributing factors in the process of killing trees. Their contribution might be the direct cause of the death of the tree, even if it was some other stress (e.g. adverse hydrogeological conditions or exposure to vehicle exhausts and de-icing salt) that was the predisposing and/or triggering factor for damage. The response of vegetation to different kinds of stress factors in the roadside environment has been studied from different points of view (Viskari, 1999).

There are also several kinds of non-exhaust particles originating from roads, vehicles, maintenance and road equipment (Gustafsson, 2001). Therefore, the needles of roadside trees will also be exposed to particles of different kinds. The deposition of road dust on needles has been shown to have detrimental effect (Flückiger, et. al, 1977). When checking the occurrence of particles on needles from the field site used in this thesis, it became evident that there are a large amount of different kinds of particles that have deposited on the needles in the roadside (figure 20).

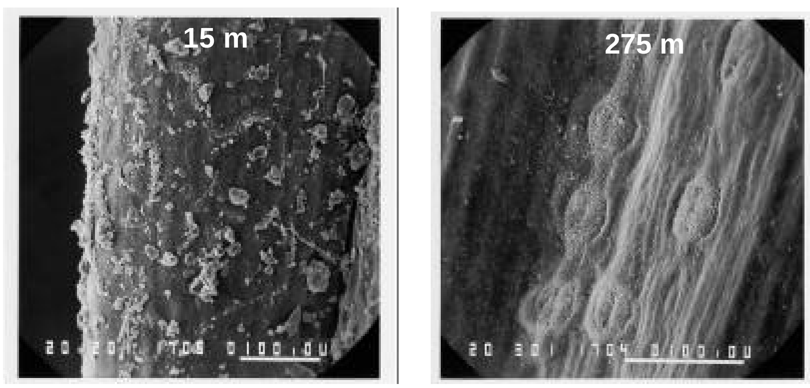

Figure 20 *Particle deposited on needles of Norway spruce as magnified by an electrone microscope (SEM). The white scale line represents 100 µm. The needle in picture to the left has grown 15 m from the highway and the needle in the right picture has grown 275 m from the highway. The 4.5 year old Norway spruce plants were planted in May 1998 and the current year needles were sampled in February 1999. The SEM-investigation was performed by Eeva-Liisa Viskari, Tampere Polytechnic and Kuopio University.*

Many of the possible responses to the described environmental problems can actually go hand in hand with responses to traffic safety measures. For instance, spray suppression systems on the vehicles would not only decrease the air borne exposure to salt, but also have good effects on visibility (Sandberg, 1980). A safety zone next to the roads can also be used for environmental protective installations and finally when trees with symptoms of salt damage are removed from the roadside the visibility in the sides of the roads increases.

Conclusions

It can be concluded that a large part of the salt that is applied on the road surface will be transported by air and deposited on the ground in the roadside. While the vast majority of the salt will be deposited within some tens of metres of the road, some may still be wind transported several hundred metres away. The wind direction plays an important role for the deposition already at a distance of some ten metres from the road. Wind speed influences the distance to which the salt is transported.

Chloride concentration in unwashed needles collected after the salting season is positively related to the bulk deposition of Cl during the exposure. The degree of damage of Norway spruce seedlings to salt exposure can be described by a sigmoid curve of response to the Cl concentration in needles.

To fulfil the Environmental quality objectives and the requirements of the Environmental Code, the road-keeper needs to follow up the de-icing activities and their environmental impacts.

Future research

This thesis has resulted in several indications, many of which might not be statistically possible to generalise into all possible roadside conditions. However, some indications seem to be interesting enough to warrant further studies.

How can the pathway of salt between the road and roadside environment be cut off?

How do really the external factors, that are aggravating the damage to vegetation work?

How can the exposure of the roadside environment to de-icing salt be predicted?

Acknowledgements

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The list could be made very long, but there would probably still be several others who also deserve my sincere gratitude for different reasons. So, to all of you who are not mentioned here by name, such as the land-owners of the field sites, the personnel at the library, people within the road administration, the personnel at the plant nursery, etcetera – without your help, this work would have been so much more difficult, Thanks!

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Definitions

Whithin the environmental sciences there are of course many expressions and notions that are used in different ways. Sometimes there may be inconsistencies in the way in which some of these very important words are used, especially when comparing their use in different disciplines. In order to avoid misunderstandings in this thesis work, I have included a dictionary that clarifies definitions of important concepts that I use within the work. There may be some inconsistencies between the use of the definitions in the early papers included and this list. That should be seen as a result of the scientific evolution of the author.

Expression	Definition
Accessibility	The ease at which citizens, the business community and public organisations can bridge distance in society (Transport policy… 1997)
AADT	Annual average daily traffic. Expressed in vehicles per day.
Aerosol	An assembly of liquid or solid particles suspended in a gaseous medium for a period long enough to enable observation or measurement
Anti-icing	See de-icing action
Biosphere	The part of the world in which life can exist including parts of the lithosphere, hydrosphere and atmosphere
Chlorosis	A yellowish to whitish general discolouration, associated with deficient production or breakdown of chlorophyll (Butin, 1995)
Consequence	Something produced by a cause or necessarily following from a set of conditions
Damage	A loss or harm resulting from injury to person, property, or reputation
De-icing action	The European COST 344 action ”Improvements to snow and ice control on European roads and bridges” differentiates between the concepts of de-icing and anti-icing (Holldorb, 2000). De-icing is defined as salting that is carried out *after* the accumulation of snow and ice while anti-icing is defined as salting procedure to *prevent* snow and ice formation by lowering the freezing point of

	the solution on the road surface. In this thesis de-icing is used in the sense of both these concepts.
Dieback	The death, often progressive, of tissues so that the extent of the living crown, root system, or cambium around a wound is reduced (Butin, 1995)
Driving force	Societal needs and activities leading to a pressure on the environment
Environmental quality objectives	Description of the qualities that our environment and our common natural and cultural resources must have in order to be ecologically sustainable.
Environmental quality criteria	The Swedish Environmental Protection Agency's Criteria for Environmental Quality Assessments constitute a system of classification which facilitates the interpretation of environmental data. The system can be used to determine whether measured values are low or high in relation to either a national average or baseline readings.
Environmental quality standards	Environmental quality standards shall specify the levels of pollution or disturbance to which the population may be exposed without any risk of significant damage or to which the environment or nature may be exposed without any risk of significant detriment (The Environmental Code, 1998)
Environmental pressure	The emission of a pollutant, potentially influencing an environmental state and thereby causing an environmental effect.
Environmental state	The condition (state) of an environmental component at a specific time.
Environmental effect	The amount of change within an environmental state induced by a specific environmental pressure.
Evaluation	Answers the question: "why something has happened?" (System med indikatorer… 1999). See also monitoring.
Exposure	Accessibility to anything that may affect, especially detrimentally
Factor	A fact or situation which influences the result of something
Impact	A powerful effect (figurative) that something, esp. something new, has on a situation, system or person.

Indicator	Forecastable quantitative variable, usually with target value representing an objective, which symbolises environmental or other impacts of transport infrastructure plans (including ordinal scales, e.g. low, medium, high) (COST 341) European Environment Agency (EEA) classifies indicators in four groups: Type A) Descriptive indicators, Type B) Performance indicators, Type C) Efficiency indicators, Type D) Total welfare indicators,
Limit value	A value that must not be exceeded (Eriksson, 1995)
Model	In order to study a system scientifically, we have to make assumptions about how it works. These assumptions, which usually take the form of mathematical or logical relationships, constitute a *model*, that is used to try to gain some understanding of how the corresponding system behaves (Law and Kelton, 1991).
Monitoring	Long-term, standardized measurements and observations in order to define status and trends. See also Survey. Answer the question: ”What has happened” (System med… 1999).
Necrosis	Death of cells or tissues (Butin, 1995)
Policy target values (PTVs)	Politically determined steps along the way towards sustainability reference values (SRV)
Pre-wetted salt	A saturated solution such as sodium chloride or calcium chloride is added to standard road salt before spreading. This provides a mechanism for the salt to adhere to the road (Holldorb, 2000).
Residual salt	Amount of salt remaining on the road surface at a specific point of time.
Road condition	The actual surface condition of the pavement depending on weather conditions, e.g. in winter (Holldorb, 2000).
Roadside	The edge of a road and the strip of land along a road.
Road Weather Information systems (RWIS)	Electronic monitoring outposts located throughout the road system. Provide data on wind speed, air and ground temperature and rainfall (Holldorb, 2000).
Salt spreading	Action consisting of spreading salt on the road surface to fight

	against or limit slipperiness (Holldorb, 2000).
Slush	Snow with a lot of water (Holldorb, 2000).
Splash	The water thrown away in the forward and side directions from the tire-road interface. It consists of relatively large droplets that are not caught by the air streams around the vehicle to any large extent (Sandberg, 1980).
Spray	Is thrown out by centrifugal action tangential to the tire tread and a great portion will break down into small droplets with low sinking speed, when hitting other parts of the vehicle. The spray is easily caught by the air streams and may persist in the air wake behind the vehicle for a long time (Sandberg, 1980).
Spread rate	Amount of de-icer/anti-icer or gritting material per area spread in one operation (Holldorb, 2000).
Survey	An intensive program of finite duration to measure and observe the quality of an environmental component for a specific purpose. See also monitoring.
Sustainability reference values (SRV)	A target level of environmental quality from the perspective of sustainable development (Smeets and Weterings, 1999)
Symptom	Distinct sign of a disease, characterized by external or internal alterations in an organism following the activity of a damaging agent (Butin, 1995).
System	A system is a structure presumed to exist in the real world. It is thought to possess characteristic properties, and to consist of interconnected components. The components are meaningfully arranged, in that they function together as a whole
Systems analysis	An approach consisting of: a way to investigate how to best aid a decision- or policymaker faced with complex problems of choice under uncertainty, a practical philosophy for carrying out decision-oriented multidisciplinary research, and a perspective on the proper use of the available tools (Quade and Miser, 1985).
Target value	A specific goal or objective expressed in quantitative terms. Examples of target values are the environmental quality standards. See also Sustainability reference value (SRV) and Policy target value (PTV)
Technosphere	All those aspects of the physical environment that have been

	created or altered by humans.
Verge	The strip (shoulder) of land beyond the road surface and pavement, but within the road boundary.
Winter maintenance	Totality of measures by the maintenance engineer to deal with snow and ice conditions, to ease traffic congestion and to maintain traffic safety in winter weather (Holldorb, 2000).

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