Long-Term Effects of Deicing Salt on the Roadside Environment

Part I: Forestry

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The effects of winter road maintenance constitute a complex system of many interrelationships. One of these relationships is the effect of deicing salt on vegetation. Such effects are described in the form of a DPSIR (Driving force, Pressure, State, Impact, Response) model. According to the model, 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 kinds of impacts (I), which may require some kind of response (R). The impacts of deicing salt on roadside vegetation are grouped into three spheres of interest: the public, landowners, and ecology. In Sweden, the Environmental Code requires that the Swedish National Road Administration work to understand how these complex systems operate and to take active measures to prevent damage to human health and the environment. This mandate requires knowledge of each DPSIR model element as well as the relationships between the elements. So far, research on this topic has resulted mainly in model indicators that cannot be used easily by road administrators. It is therefore of great importance to be able to assign adequate indicators to all levels of the model and to monitor these indicators on both a temporal and spatial scale that facilitates responding with the proper actions. To establish an environmentally sustainable winter road maintenance system, it is also crucial to establish the long-term tolerance limits of human health and nature as the base for salting strategies.

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During the winter season, both road safety and road network accessibility must be maintained to acceptable levels. The overall goal of Sweden's transport policy is divided into five subgoals or objectives.

1. An accessible transportation system,
2. High transportation system quality,
3. Traffic safety,
4. A good environment, and
5. Positive regional development.

Reconciling the first three goals with that of maintaining a good environment is a delicate matter involving conflicting interests.

Road administrators have had a long-term interest in the different impacts associated with winter road maintenance operations, and much effort has been spent on understanding the relationships between their actions and their effects on friction, speed, stopping distance, fuel consumption, corrosion, and traffic safety (*1*). But when developing an integrated management system for winter road operations, it is important to appraise all related consequences, including those on the environment.

Many studies have been conducted on the effects of deicing salt usage on the environment (e.g., vegetation, groundwater quality, and soil chemistry) (*2–7*). It has now become vital that the Swedish National Road Administration (SNRA) understand the integrated workings of the winter road maintenance system, including its component interactions, with a view toward protecting human health and the environment against damage or detriment. In fact the 1999 Swedish Environmental Code requires it. Under the same law, road administrators are required to implement protective measures and any other precautions that may be necessary to prevent or mitigate damage or detriment to human health or the environment as a result of any winter road activity or measure (SFS 1998: 808, The Environmental Code, Statute Book of Sweden).

The aim of this study is to describe, from the viewpoint of the road administrator, that part of the winter road maintenance system that involves the interrelationship between deicing actions and damage to vegetation and to present a model of that system, which will allow the involved components and processes to be identified and monitored.

Winter Maintenance Operations

Goals of Transport Policy and Environmental Law

In June 1998 the Swedish Parliament adopted a new transport policy on the basis of the government bill titled *Transport Policy for Sustainable Development* (SFS 1997:652, Statute Book of Sweden). The overall goal of the transport policy is divided into the five subgoals listed earlier: an accessible transportation system, high transportation system quality, traffic safety, a good environment, and positive regional development.

For the first objective, an accessible transportation system, accessibility is defined as the ease with which citizens, the business community, and public organizations can bridge distance in society.

The fourth objective, a good environment, is defined in the following requirement: "the design and function of the transport system will be adapted to the requirements for a good and healthy living environment for everyone, where natural and cultural environments will be protected against damage." Good management of land, water, energy, and other natural resources must be promoted. Also, the government bill on which the new transport policy is based establishes that long-term emissions goals be based on the tolerance limits of human health, environment, and nature (Government Bill 1997/98:56, Transport Policy for Sustainable Development).

The Swedish Roads Act (SFS 1971:948, Statute Book of Sweden) states that roads shall be held in a satisfactory state by maintenance and other measures. This mandate does not, however, overrule the requirements of the Environmental Code for the maintenance of roads (Government Bill 1997/98:90), which requires that its provisions be applied in such a way as to ensure that human health and the environment are protected against damage and detriment, whether caused by pollutants or other impacts, and that the best available technology be used in connection with professional activities (SFS 1998: 808, The Environmental Code, Statute Book of Sweden).

Winter Road Maintenance Effects

A key issue in the road management sector is ensuring that limited funds are spent to have the greatest impact within various applicable constraints (*8*). The winter road maintenance manager must achieve a balance among many considerations, including accessibility, safety, comfort, travel time, and the environment (*9*).

The system of winter road maintenance operations and their effects on traffic safety and road accessibility have been described by Wallman et al. (*1*). Maintenance measures are identified as the central component of the system. In the Wallman et al. model, each measure leads to a large number of interrelated effects. The influence of different winter road conditions on speed and traffic flow is discussed by Wallman in a paper in this proceedings. Winter road maintenance effects are divided into three categories in the Wallman et al. model: costs for the road user, costs for the road manager, and environmental costs (Figure 1). The most cost-effective measures are chosen after comparing the different costs (*1*).

Today the operating requirements of winter road management in Sweden are an aggregated function of road user costs and road manager costs (*9*).

Roadside Exposure to Salt

Deicing salt is used to prevent slippery conditions by forming a brine layer on the road surface that prevents snow and ice from bonding to the surface. In this deicing action system, vehicles play an important role by forming slush and then forcing the salt-laden slush off the road. Thus the dispersion of salt from the road is built

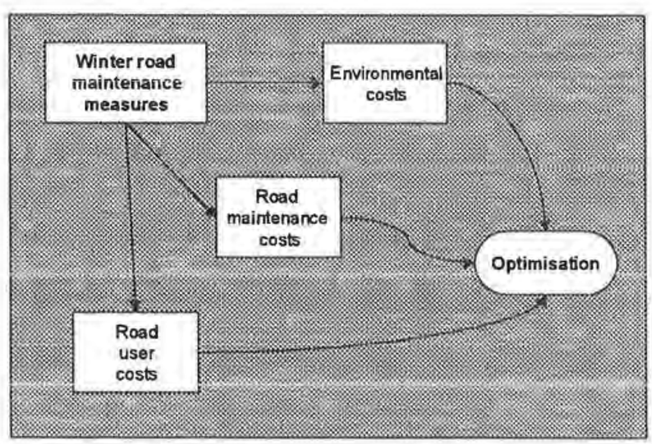

FIGURE 1 Winter maintenance operations system and effects [simplified after Wallman et al. (*1*)].

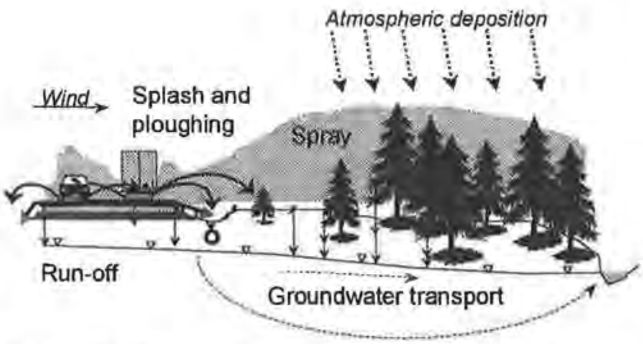

FIGURE 2 Conceptual model of salt transport mechanisms and salt pathways from the road.

into the system, as well as the exposure of the roadside environment to salt.

Deicing salt follows one or more of several pathways from the road, each of which is coupled to separate mechanisms that are regulated by a set of factors (*10*). The major mechanisms are runoff, splash, ploughing, wet spray, and dry crystal aerosols (Figure 2). The factors that regulate to what extent one or more of the mechanisms contribute to the total transport of salt from the road are traffic characteristics (type, speed, and intensity), road surface characteristics, salting management practices (amount, technique, and timing), meteorological factors, and other site-specific factors (including topography and hydrogeology).

A model or airborne salt deposition next to roads should be a function of the sum of each transport mechanism (e.g., splash and spray) and background deposition (Figure 3). The model variables should also be related to the factors regulating the transport mechanisms rather than a mere arbitrary function that can predict values within a specific range (*10*). The deposition pattern resulting from this model constitutes one aspect of the roadside's exposure to salt.

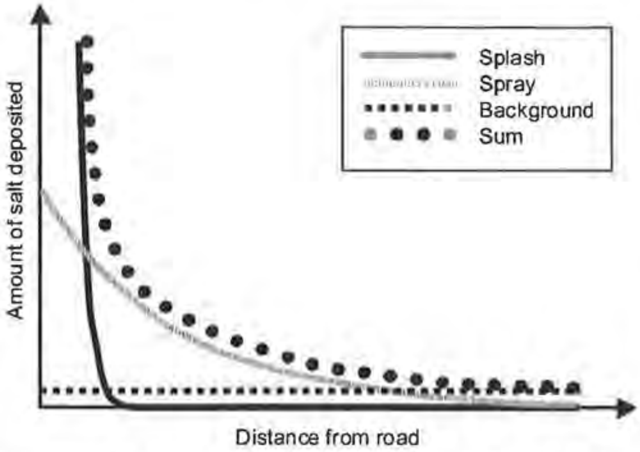

FIGURE 3 Model of total salt deposition in the roadside environment.

Environmental Effects, Damage to Trees

In many studies, damage to trees (both in field studies and under controlled conditions in laboratories) has been shown to occur both when salt is applied to the soil as well as when it is deposited onto the foliage (*2, 3*). Symptoms in coniferous trees are often described as needle browning and needle loss (*11*). Some trees are able to compensate for the damage by producing new shoots, but when the damage is too great, this is not possible (*10, 12*).

The consequences of this damage are many. One is the impact on biota in itself; another is the effect on the landscape. The impact of deicing salt on conifers is a result of a complex interplay of many causal relationships (e.g., loss of needles leading to lower photosynthetic capacity; osmotic stress through the increased amount of salt in soil water leading to inhibition of water uptake; and stress avoidance requiring energy expenditure). Most of these effects will in the end result in diminished growth of the tree stand and can also predispose the tree to damage from fungi or insects. Such effects have been described by, for example, Pedersen and Fostad (*11*). It is often difficult to distinguish among the different stress factors: one may have predisposed the tree to damage, another may have triggered the damage, and yet a third may have contributed to the actual killing of the tree (*13*).

The extent of tree damage is governed by a kind of dose-response function. In this case the dose is represented by salt exposure and the response by the degree of damage to vegetation. For some species the function has been suggested as S-shaped (Figure 4) in comparing the concentration of chloride in needle tissue to the extent of damaged needles (*14*). Many investigations have been conducted of the relationship between chloride amounts in needle tissue and the extent of visible damage symptoms. For example, comprehensive compilations have been published by Dobson (*3*) and Brod (*15*).

A field investigation in Sweden was performed as a potted plant experiment to check the extent and pattern of damage to two-year-old Norway spruce (*Picea abies*) seedlings in a deicing salt-exposed environment next to a

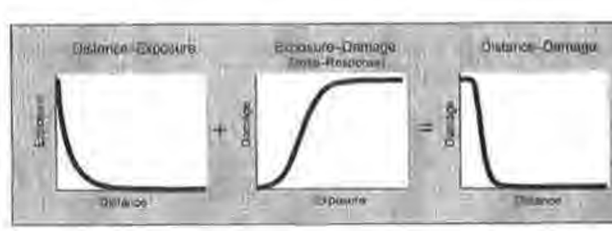

FIGURE 4 Theoretical functions of exposure to salt and susceptibility to salt damage give the pattern of damage in the roadside environment.

highway (*16*). The pattern of damage (Figure 5) was consistent with the theoretical curve in Figure 4. One should keep in mind, however, that the roadside environment is also exposed to many other stress factors (*6*).

Cost of Salt Damage to Trees

Some attempts have been made to calculate the cost of salt damage to trees. In a TRB Special Report (*2*) the cost was calculated as the cost of removing a dead tree and planting and maintaining a young tree in its place. On the other hand Vitaliano (*17*) represented the cost as the lessened demand for viewing a scenery of less aesthetically pleasing trees in areas heavily impacted by road salting. The two cost assessments focus on different aspects of the same problem: whereas the first considers the costs for mitigating the problem of dead trees, the second considers the costs of degraded landscape scenery. Both assessments are concerned with the costs of damage that has already occurred.

Randrup and Pedersen (*18*), however, focus on the costs of damage prevention, which they define as the estimated cost of replacing the soil of urban trees and of protecting trees using plastic-covered straw mats.

As concluded in a Finnish investigation (*19*), the main problem posed by deicing salt-induced damage is the discoloration of young Scots pine (*Pinus sylvestris*) trees. In an extensive Norwegian program studying the effects of deicing salt on soil, water, and vegetation, the most vulnerable species studied was Norway spruce (*11*). The most extensive damage reported in the Norwegian study was caused by the uptake of salt through the tree roots. In some states in the United States, 5 to 10 percent of roadside trees within 100 ft of the pavement edge along some sections of salt-treated primary highways exhibit signs of salt-related decline (*2*). In two Swedish studies (*20*), many sections along the primary highways exhibited damage to coniferous trees amounting to more than 70 percent of vegetation at the individual tree level.

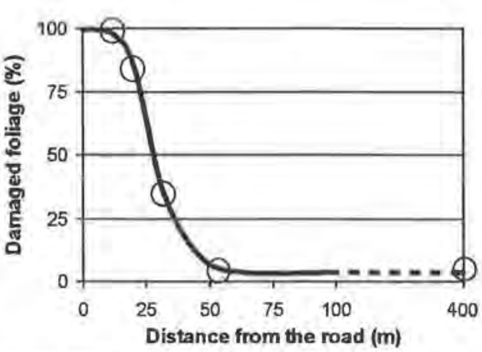

FIGURE 5 Pattern of damage to Norway spruce seedlings in a field case study.

Roadside trees and shrubs in Sweden have to some extent been removed as a road safety measure (Figure 6). This action also removes the symptoms of salt-damaged trees.

Forestry: A Process, Not a Steady State

Forestry should be thought of as a process rather than a steady state. While one effect of roadside exposure to deicing salt is a lower forestry yield, a potentially more significant long-term consequence may manifest itself during reforestation, as seedlings and young plants are much more sensitive to salt exposure than older trees. Reforestation may therefore be virtually impossible within a zone of up to several tens of metres from the road. In many places this zone extends beyond the road reserve area (i.e., the right-of-way boundary) and therefore may affect the land next to the road. If reforestation is not possible, the landowner is subjected to a forced change of land use (Figure 7), which will probably lead to different legislative possibilities concerning damage claims than would the impact of diminished growth along the roadside.

The economic consequences of these factors must be considered lest potential claims for damages by landowners come as an unpleasant surprise to road administrations.

SYSTEM DESCRIPTION

The Swedish Environmental Protection Agency has established a system for the follow-up of national environmental quality objectives (*21*). The system uses defined indicators for each part of the process following the internationally accepted DPSIR (Driving force, Pressure, State, Impact, Response) model (Figure 8). Societal needs

FIGURE 6 Removal of roadside trees and shrubs to eliminate symptoms of salt-damaged trees and cutting and mowing of the roadsides to promote roadside biodiversity.

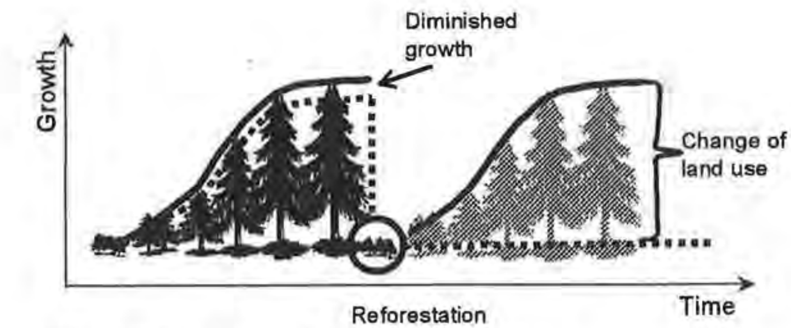

FIGURE 7 Implications for forestry, seen as a process.

and activities can be viewed as driving forces (D) that lead to a pressure (P) on the environment. This pressure may change the state (S) of some environmental components, which in turn can lead to impacts (I) on an area such as human health or nature. Finally, society will respond (R) in some way to combat the problem in one or several of the model's earlier stages (*21*).

Using the DPSIR model, the use of deicing salt and damage to vegetation could be described as follows (Figure 9):

- The driving force (D) is the transportation need of citizens and industry, formulated as subgoals (e.g., accessibility, quality, and safety). To be achieved, these subgoals require the use of deicing salt (*9*).
- The pressure (P) is the deicing salt that follows different pathways from the road to somewhere in the environment.
- The state (S) of the roadside vegetation is dependent on, for example, salt concentration on the plants, in the plants, in the soil, and in the soil water.
- The impacts (I) of the pressure-induced state are, for example, degraded landscape scenery, diminished tree growth (in the worst case forcing a change of land use), trees predisposed to secondary pests, and an altered species composition along the road.
- The societal responses (R) can influence all other levels of the system (D, P, S, I).

There are two elements in Figure 9 that are not included in the original DPSIR model (Figure 8). The first, indicated in the oval between driving force (D) and pressure (P), represents the activity induced by the driving force and causing the pressure. In this case the action is the deicing measure.

The other Figure 9 element not included in the Figure 8 DPSIR model comprises laws, directives, policies, regulations, and contract conditions (indicated in the box at the upper right of the figure). These are partly a result of societal needs (e.g., the need for transportation is manifested in some of the goals of the transport policy), but they can also be used by society as a toolbox for responding to all DPSIR model stages. Finally, this element also governs liability issues surrounding different impacts (I).

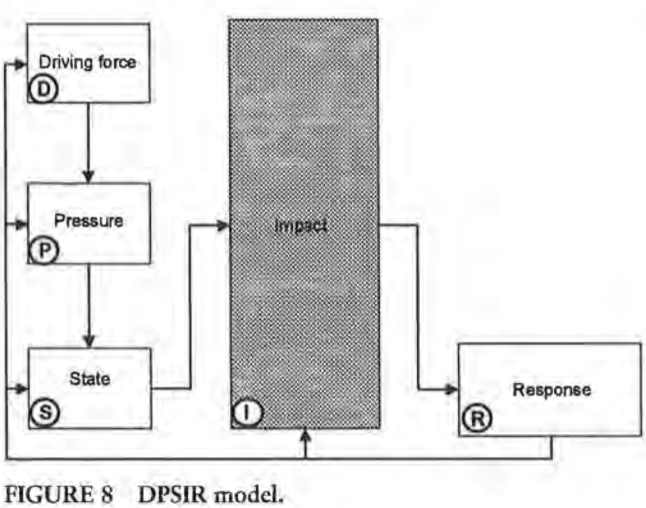

FIGURE 8 DPSIR model.

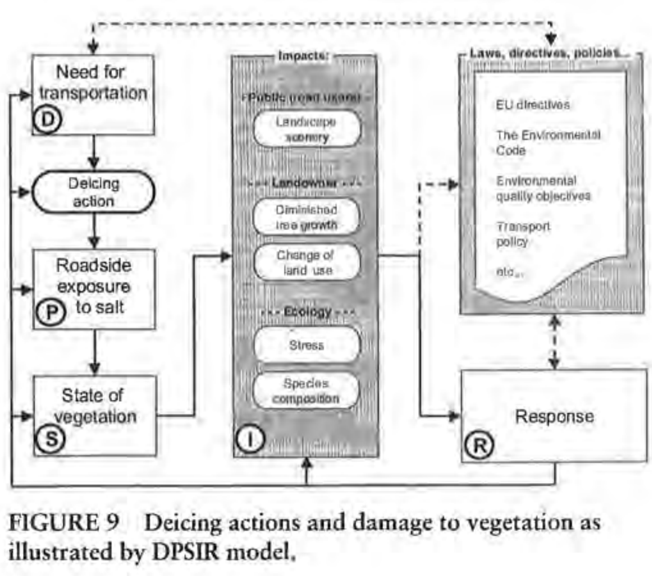

FIGURE 9 Deicing actions and damage to vegetation as illustrated by DPSIR model.

Each component in the DPSIR model (Figures 8 and 9) is connected by arrows representing the links and relationships between the components:

- The relation between the need for transportation (D) and deicing actions taken is governed by, for example, requirements in winter road maintenance operating rules (9) and available technology and methods.
- The relation between deicing actions and roadside exposure to salt (P) is dependent on such variables as the amount of salt used, salt type, speed and intensity of the traffic, road surface characteristics, wind speed and direction, and distance from the road (Figures 2 and 3).
- The relation between roadside exposure to salt (P) and the state of vegetation (S) can be described by a dose-response function (Figure 4) dependent on such variables as type of exposure, type of vegetation, ability to avoid or tolerate stress, and other contributing stress factors.

Discussion of Results

Responsibilities and Sustainability

Chapter 2:2 and 2:3 of the Environmental Code in Sweden (SFS 1998:808, The Environmental Code, Statute Book of Sweden) outlines the requirements of having knowledge of the impacts of one's activities and implementing protective measures in order to prevent impacts on human health and the environment. In the instructions for the SNRA the government charged the SNRA as the representative of the state with overall responsibility for the development of and developments within the road transport system (SFS 1997:652, Statute Book of Sweden). This sectoral responsibility, together with the rules in the Environmental Code, places a large responsibility on the SNRA. This requires that research and development efforts be focused on the most relevant relationships within the system of winter maintenance operations and their effects in order to avoid unpleasant surprises such as unforeseen claims for damages or judicial processes. Regarding the judicial aspect of the issue, the situation is still somewhat unclear in Sweden, since the issue has not yet been tried in the courtroom.

Environmental costs (Figure 1) also imply additional components to those described in this study. These include, for example, effects on groundwater, soil physics, and soil chemistry that not only lead to secondary impacts on vegetation but may also affect human health and the state of the natural and cultural environment. Long-term effects of the use of deicing salt on groundwater and surface waters are described by Thunqvist in a paper in these proceedings.

Tolerance Limits and Indicators

In today's winter operations in Sweden, the general recommendation is to "use as little salt as possible." It can be argued, however, that this recommendation is not based on an environmental concern as long as the two words "as possible" are connected only to requirements for a specific road surface friction value or snow depth tolerance limit. In fact the regulations specify no environmental tolerance limits.

On the other hand the salting strategy could also be interpreted to mean "use as much salt as possible." In this case the words "as possible" should be based on the long-term tolerance limits of human health and nature, a basic concept in the government bill on which the current transportation policy is based (Government Bill 1997/98:56, Transport Policy for Sustainable Development).

So far most studies on salt tolerance limits with regard to vegetation damage have been concerned with concentrations of sodium and chloride in plant tissue (*3, 15*). From the road administrator's point of view, however, this indicator is not very useful. A more important indicator would be the relation of deicing action (amount, method, technique, and timing) to the occurrence of damage, which would ultimately reveal what deicing strategy should be used on each individual occasion.

The extent of deicing damage has been classified in numerous investigations, but these have been devoted almost exclusively to only one impact—the stress compartment (Figure 9). In comparing different investigations of damage rates, it is evident there is a need for a uniform damage rating system, as many different damage rating systems make comparisons difficult. What is more important, however, is that adequate indicators be assigned to all impacts at all system levels (driving forces, pressures, states, and responses).

Robinson et al. (*8*) 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." It could be added that a crucial challenge for the scientific community is to find the key parameters and indicators for each of the system's different levels (driving forces, pressures, states, and responses) that can be understood and utilized by road managers. Monitoring the system on the proper spatial and temporal scales using adequate indicators will not only strengthen the scientific understanding of the system's ecological effects, but it will also increase the potential of taking appropriate measures that will improve the sustainability of the system.

Conclusion

Deicing salt usage and its effects on vegetation are complex; however, the new legal situation in Sweden requires the road authority to possess a proper understanding of this system.

A suitable model of the system is the DPSIR model, which takes into account the entire process from the societal need for transportation to actual impacts to required responses. To acquire the knowledge needed to take effective countermeasures against undesired impacts, the system must be monitored using adequate indicators at all its levels.

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