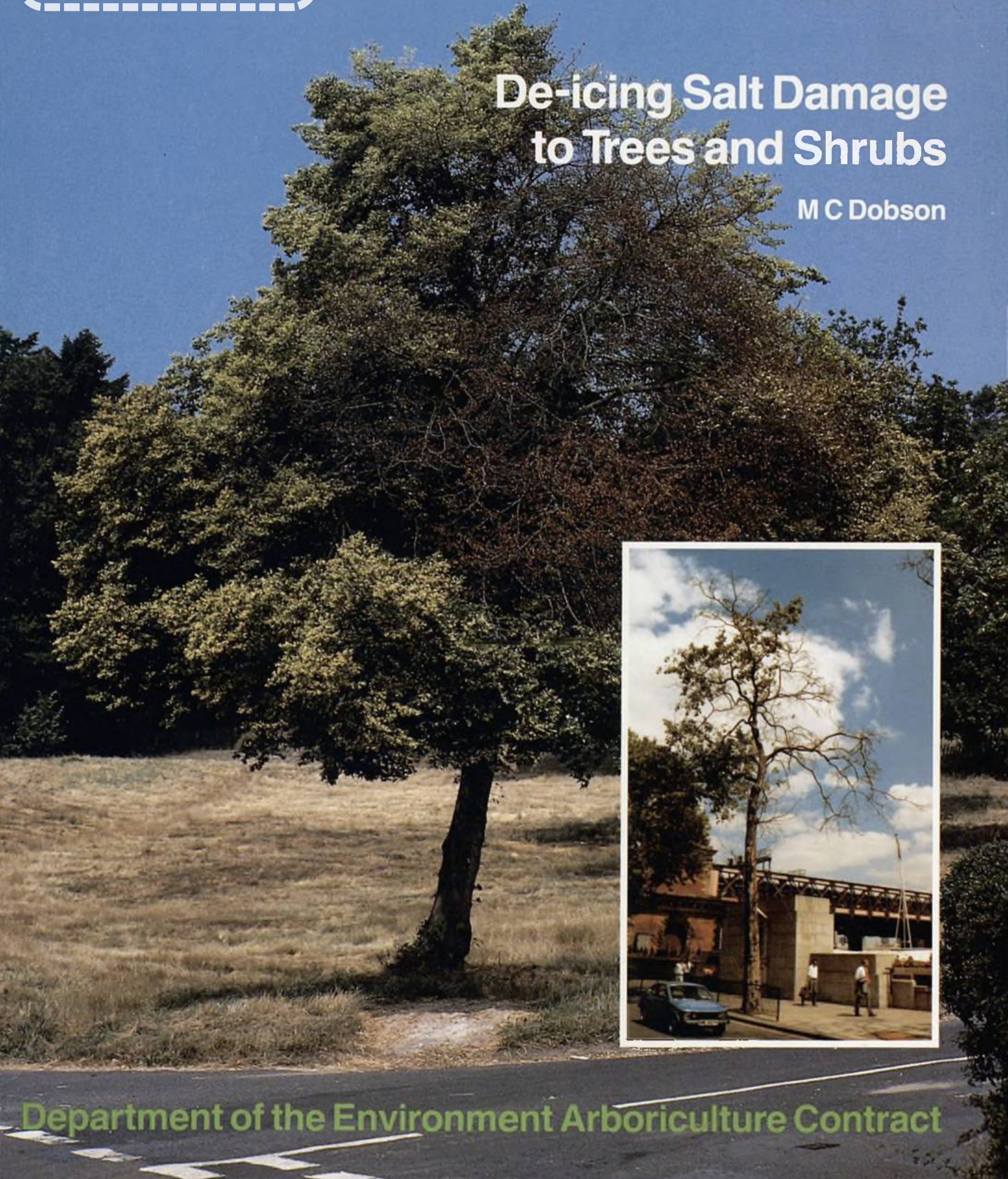
Forestry Commission

Bulletin 101

De-icing Salt Damage to Trees and Shrubs

M C Dobson



Department of the Environment Arboriculture Contract

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De-icing Salt Damage to Trees and Shrubs

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Forestry Commission

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Front cover: Crown dieback of lime. A pile of de-icing salt was placed beneath the crown of the tree in winter (the remains can still be seen) and resulted in its eventual death. *(J. N. Gibbs)* *Inset.* Salt-damaged London plane, Victoria Embankment, London. *(P. Holloway)*

Contents

De-icing Salt Damage to Trees and Shrubs

Summary

The damage caused by de-icing salt is a serious, but often underestimated, problem which affects substantial numbers of roadside trees and shrubs both in Britain and abroad. This Bulletin has resulted from an extensive review of the world literature on the subject; the findings fall into four distinct categories which comprise its four chapters. Chapter 1 describes the early investigations that led to the recognition of salt as a cause of street tree death, and outlines the current situation in Britain. The symptoms of salt damage are described, with distinctions being made between damage caused by salt spray and salt-contaminated soil for both deciduous and evergreen species. In addition, the available data on foliar concentrations of chloride and sodium associated with leaf symptoms are summarised.

In Chapter 2 the methods used for evaluating salt tolerance are described and the mechanisms of salt tolerance are outlined. A comprehensive list of woody plants with their reported salt tolerance rankings is presented. These data often show marked inconsistencies, some species being classed as tolerant by one author and as susceptible by another. The reasons for this are discussed.

The mechanisms of salt toxicity are described in Chapter 3, and the relative importance of osmotic and specific ion effects in the development of injury symptoms are discussed.

The methods that are being used, or could be used, to reduce de-icing salt damage to trees are evaluated in Chapter 4. It appears that reductions in salt usage of the order of 60% could be achieved in the UK if salt was stored and spread with greater efficiency. Alternatives to using salt include roadway heating, and the use of abrasives or salt/abrasive mixtures or other de-icing agents such as sulphates, urea, alcohols and glycols, methanol and calcium magnesium acetate (CMA). Although expensive, CMA is the most promising of these because of its good de-icing capability and its low phytotoxicity.

Flushing soil with water to remove salt and the addition of gypsum ($CaSO_4$) and fertilisers appear, from the literature, to be the best treatments for salt-contaminated soil. However, there is little experimental and no practical experience in the use of these ameliorants in Britain. The potential for amelioration through design and engineering is considered.

Les Dégâts par le Sel Utilisé pour Dégeler les Routes sur les Arbres et les Arbustes

Résumé

Les dégâts causés par le sel utilisé pour dégeler les routes représentent un problème important et souvent sous-estimé, qui affecte un nombre considérable d'arbres et d'arbustes situés en bordure des routes, en Grande-Bretagne et à l'étranger. Ce Bulletin est le fruit d'une étude détaillée faite à partir de tous les documents qui existent sur ce sujet dans le monde entier; l'analyse est divisée en quatre sections correspondant à quatre chapitres différents. Le chapitre 1 décrit les premières recherches qui ont prouvé que le sel peut entraîner le dépérissement des arbres plantés dans les rues et il examine la situation actuelle en Grande-Bretagne. En outre, ce chapitre passe en revue les symptômes typiques observés sur les arbres à feuilles caduques et les arbres à feuilles persistantes, plantés sur des sols contaminés par le sel et exposés aux projections de sel. Enfin, cette première section résume la relation entre la concentration foliaire de chlorure et de sodium et les symptômes observés sur les feuilles.

Le chapitre 2 se concentre sur les méthodes utilisées pour évaluer la tolérance et les mécanismes de tolérance vis-à-vis du sel. Il présente également une liste très complète de plantes ligneuses ainsi que leur degré de résistance au sel. Ces données appraissent parfois illogiques car suivant les auteurs, la tolérance des espèces varie considérablement. Le chapitre explique ces différences d'opinions.

Les mécanismes de toxicité du sel sont abordés dans le chapitre 3, ainsi que l'importance des phénomènes osmotiques et de l'action de certains ions spécifiques sur le développement des symptômes observés.

Le chapitre 4 examine les méthodes utilisées ou celles qui pourraient être utilisées pour limiter les dégâts causés par le sel sur les arbres, lorsque les routes sont salées. Il semble que le Royaume-Uni pourrait économiser 60% du sel utilisé actuellement si celui-ci était conservé dans de meilleures conditions et s'il était répandu sur les routes de manière plus efficace. Il existe également d'autres solutions qui pourraient remplacer le sel comme par exemple le chauffage des chaussées, l'utilisation de produits abrasifs ou de mélanges de sel et de substances abrasives ou enfin, l'utilisation d'agents pour dégeler les routes comme le sulfate, l'urée, l'alcool, le glycol, le méthanol et l'acetate de magnésium/calcium (A.M.C.). Bien qu'il soit très coûteux, l'A.M.C. est l'une des solutions les plus prometteuses en raison de son excellente capacité à dégeler et de sa faible phytotoxicité.

Le lavage des sols à grande eau, complété par l'utilisation de gypse ($CaSO_4$) et d'engrais, semble être, d'après les informations disponibles, la solution la plus efficace pour traiter les sols contaminés par le sel. Cependant, très peu d'expériences ont été effectuées et aucun test pratique n'a été réalisé dans ce domaine en Grande-Bretagne. Enfin, la construction de routes mieux adaptées et mieux conçues est également envisagée pour remédier à la situation.

Beschädigung von Bäumen und Sträuchern durch Streusalz

Zusammenfassung

Der Schaden, der durch Streusalz angerichtet wird, ist ein ernstes und oft unterschätztes Problem, das eine hohe Anzahl von an Straßen stehenden Bäumen und Sträuchern in Großbritannien und im Ausland betrifft. Dieses Bulletin ist das Resultat einer ausführlichen Untersuchung der Weltfachliteratur, die sich mit diesem Thema befaßt. Die Ergebnisse können in vier verschiedene Kategorien aufgeteilt werden, die aus vier Kapiteln bestehen. Das 1. Kapitel beschreibt die anfänglichen Untersuchungen, die dazu führten, daß Salz als Ursache für das Eingehen von Bäumen an Straßen erkannt wurde. Außerdem umreißt es die gegenwärtige Situation in Großbritannien. Die Symptome der durch Salz entstandenen Schäden werden dort beschrieben und es wird zwischen Schäden an Laub- und Nadelbäumen unterschieden, die durch Salzsprühnebel und durch mit Salz beschmutze Erde entstanden. Die vorliegenden Daten der mit den Blättersymptomen zusammenhängenden Chlorid- und Natrium-konzentration in Blättern werden ebenfalls zusammengefaßt.

Im 2. Kapitel werden die Methoden zur Beurteilung der Salztoleranz beschrieben und die Mechanik der Salztoleranz umrissen. Dort ist eine umfangreiche Liste von holzigen Pflanzen mit ihrem entsprechenden Salztoleranzgrad aufgestellt. Diese Daten weisen oft deutliche Widersprüchlichkeiten auf; manche Arten werden von einem Author tolerant und von einem anderen anfällig genannt. Die Gründe dafür werden ausführlich beschrieben.

Die Mechanik der Giftigkeit des Salzes wird im 3. Kapitel beschrieben sowie die relative Bedeutung osmotischer und spezifischer Ionenauswirkungen auf die Entwicklung von Verletzungssymptomen.

Die Methoden, die angewandt werden oder angewandt werden könnten, um den von Streusalz verursachten Schaden zu verringern, werden im 4. Kapitel ausgewertet. Es scheint, daß der Gebrauch von Salz in Großbritannien um *ca.* 60% verringert werden könnte, wenn das Salz effektiver gelagert und gestreut würde. Alternativen zum Gebrauch von Salz sind u.a. Straßenheizung, der Gebrauch von Scheuermitteln oder einer Salz/Scheuermischung oder anderen Enteisungsmitteln wie z.B. Sulfaten, Urea, Alkohol und Glykol, Methanol und Kalzium-Magnesium-Azetat (CMA). Obwohl es teuer ist, ist CMA wegen seiner guten Enteisungsfähigkeit und niedrigen Giftigkeit für Pflanzen das vielversprechendste von ihnen.

Ausspülen der Erde mit Wasser zur Entfernung des Salzes sowie die Zugabe von Gips ($CaSO_4$) und Dünger scheint der Fachliteratur nach die beste Behandlung für durch Salz verschmutzte Erde zu sein. Es gibt jedoch wenig experimentelle und überhaupt keine praktische Erfahrung beim Gebrauch dieser Bodenverbesserungsmittel in Großbritannien. Das Potential für eine Bodenverbesserung durch Design und Technologie wird in Erwägung gezogen.

Foreword

This Bulletin represents the culmination of a Department of the Environment funded research contract to review damage to trees and shrubs from de-icing salt, and its prevention/amelioration. Its publication is timely, not only because of the recent trend towards increasing environmental awareness, but also because of its coincidence with the aftermath of the first severe winter in Britain since 1986/87. It seems likely that the continued heavy reliance on salt for keeping thoroughfares clear of snow and ice during the 1990/91 winter will once again result in the dieback and death of many thousands of roadside trees.

This situation, however, need not be accepted as inevitable. The unnecessary wastage of up to 60% of all de-icing salt purchased in the UK could be prevented by more efficient storage and spreading practices. Implementing these practices would by no means compromise present standards of service, rather, they would result in significant monetary savings; a good example of where environmental and financial gains can result from improved management.

While appropriate economies in the use of salt should be welcomed and encouraged, thought should also be given to the development and use of environmentally acceptable alternatives to salt. Calcium magnesium acetate (CMA) is one such alternative that has recently become available in the UK, which, from evidence of initial studies, deserves further critical consideration.

It is to be hoped that this Bulletin will heighten the awareness of the problems caused by the application of de-icing salt and encourage all concerned to provide a better service. I commend the report to all those who manage amenity trees and those who have the responsibility for keeping our roads free from ice and snow each winter.

Tony Baldry MP
Parliamentary Under-Secretary of State,
Department of the Environment
1 May 1991

Chapter 1

Symptomatology of De-icing Salt Damage

Introduction

Rock salt, sodium chloride (NaCl), has been used in increasing quantities since the second world war for minimising the danger to motorists and pedestrians from icy thoroughfares. With the rise in traffic volume on major and minor roads and with the expansion of the road network throughout Europe and North America, the amount of salt used for de-icing operations has increased correspondingly. In Britain, rates of application have increased sharply so that, for example, applications during the winter of 1979–80 were more than twice that of the appreciably more severe winter of 1962–63 (Figure 1.1). During winters such as that of 1979–80 total applications of salt per

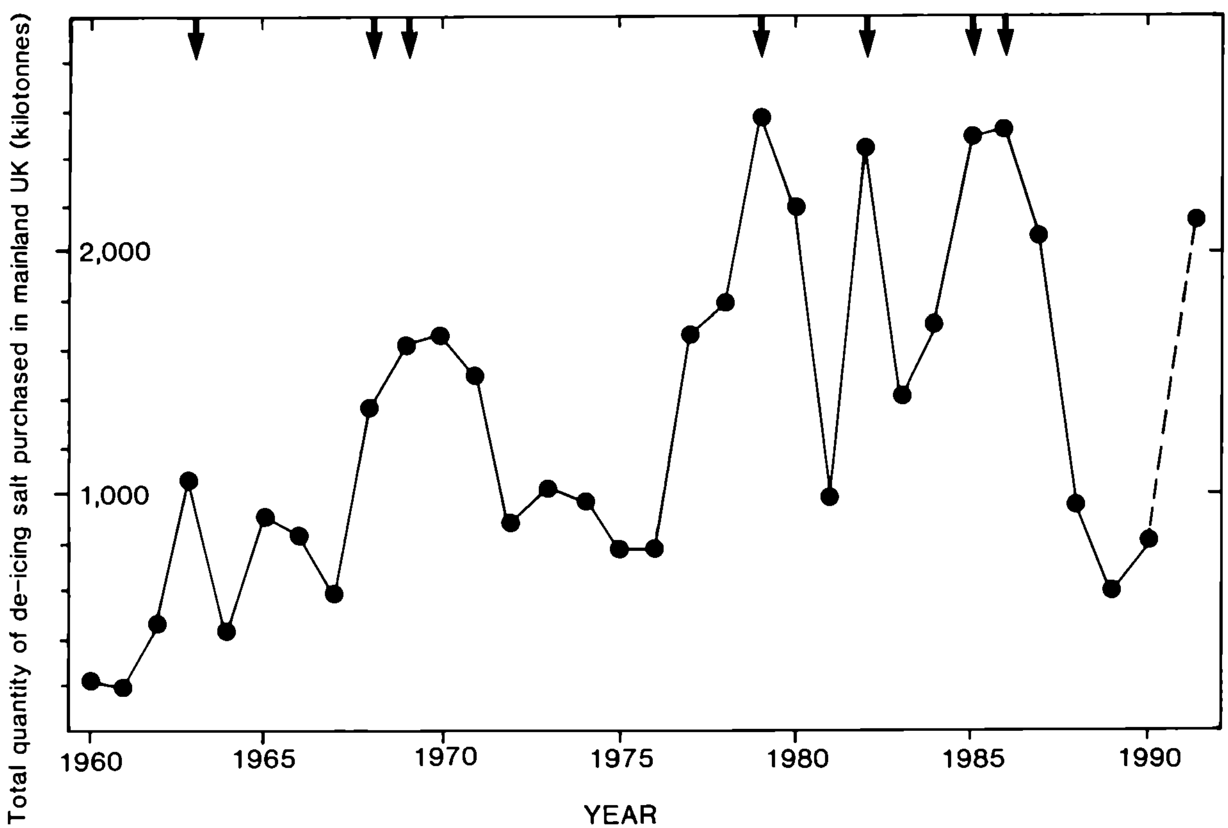

Figure 1.1 *Estimates of total quantity of de-icing salt purchased annually in mainland Britain during the period 1960-1991 (figures supplied by ICI). Arrows represent years when significant crown dieback of London plane has occurred (Gibbs and Burdekin, 1983; FC records). In the early 1960s Highway departments changed from using salt/abrasive mixtures to using pure rock salt and this may account for some of the increase in salt usage.*

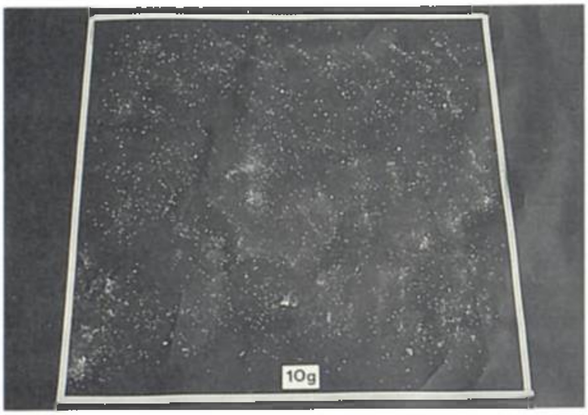

Plate 1. *Salt applied at 10 g m^{-2} as recommended by the Department of Transport (1987) for precautionary salting prior to a frost. In practice this rate is often exceeded.*

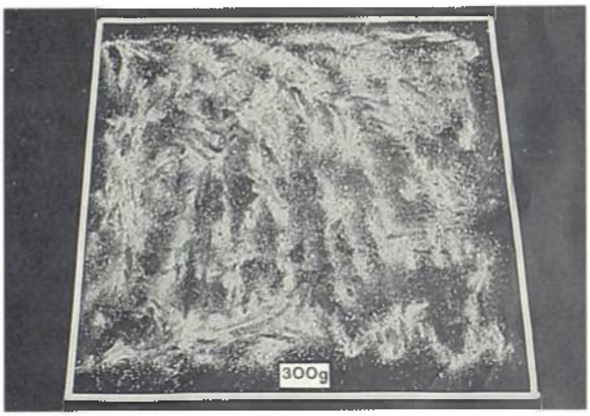

Plate 2. *The cumulative amount of salt typically applied to roads in southern England during a mild winter (300 g m^{-2}).*

Plate 3. *The cumulative amount of salt typically applied to roads in England during a severe winter (3000 g m^{-2}; Thompson and Rutter, 1986).*

square metre of roadway have exceeded 5 kg (Thompson and Rutter, 1986; see also Plates 1–3). Evidence gathered over the years has shown that these continuing annual applications of salt are having detrimental effects not only on bridge structures (Vassie, 1984) and motor vehicles (Murray and Ernst, 1976) but also on the environment, including water courses (Scott and Wiley, 1980), animals (Trainer and Karstad, 1960), and plants (Burg, 1989). Jordan (in 1971) cited by Flückiger and Braun (1981) estimated that de-icing salt applications were directly responsible for the deaths of over 700 000 trees annually in Western Europe. Today, however, the situation is probably much worse (compare Table 1.1 with Figure 1.1).

Table 1.1 Usage of de-icing salts in some European countries in tonnes.

	1965–66	*1966–67*	*1967–68*	*1968–69*	*1969–70*	*Mean*
Belgium	20 000	21 000	36 000	54 000	77 000	41 600
Finland	16 000	16 000	30 000	25 000	–	21 720
France	–	90 000	120 000	300 000	330 000	210 000
Great Britain	*900 000*	*833 000*	*586 000*	*1 318 000*	*1 625 000*	*1 052 400*
Italy	23 000	30 000	27 000	42 000	55 000	35 400
Netherlands	138 000	150 000	209 000	355 000	490 000	269 400
Poland	27 000	42 000	110 000	141 000	160 000	96 000
Spain	1 400	4 000	5 000	5 000	2 600	3 080
Sweden	82 000	108 000	88 000	109 000	95 000	96 400
Switzerland	55 000	30 000	35 000	66 000	95 000	52 200
West Germany	631 000	515 000	537 000	953 000	1 800 000	887 200

Table after Dimitri (1981).

History of salt damage

In the USA effects of salt on trees adjacent to streets were first recognised in the 1940s. Strong (1944) reported that calcium chloride ($CaCl_2$) applied to dirt roads in summer as a dust palliative caused severe leaf scorch, twig dieback, and even death of roadside trees. Salts (NaCl and $CaCl_2$) applied to icy roads in winter were also considered to be a major cause of damage to street trees (French, 1959). Experiments were initiated in 1952 to investigate the possible role of de-icing salt in roadside tree injury in Massachusetts and were reported by Holmes (1961). He found that applications of sodium and calcium chlorides to the soil beneath several tree species for seven consecutive winters produced no injury symptoms. This led Holmes to conclude that "winter road salting probably does no great harm to trees in Massachusetts". However, shortly afterwards Holmes and Baker (1966) reported the results of further work conducted on roadside sugar maples (*Acer saccharum*). Analysis of leaves from trees along salted roads showed that trees with little or no foliar injury had low chloride (Cl^-) levels (0.05–0.6% of oven dry weight) whereas those with severe leaf scorch had chloride levels exceeding 1%.

At the same time similar work was being conducted in the adjacent state of New Hampshire and in 1964 Lacasse and Rich reported the existence of a strong correlation between distance of sugar maples from roadsides and the severity of damage symptoms. Sodium (Na^+) levels in soil, leaves, and twigs were elevated within 30 ft of the roadside and were related to tree health but tree age, pathogens, and environmental stresses other than salt, were not. Further evidence suggesting that salt was important in causing damage to roadside trees was provided by Rich (1971) who found that 93% of maples along unsalted roads in New Hampshire were healthy but that only 12% were healthy along salted roads.

During the same period, concern in Germany was growing over unexplained 'Straßenbaumsterben' (street tree death) particularly of lime (*Tilia cordata*) and horse chestnut (*Aesculus hippocastanum*). Ruge and Stach (1968) examined damaged trees of these species in Hamburg and found that symptoms of dieback occurred when Cl^- levels were greater than 1% of the dry weight of the leaves.

Conclusive evidence that de-icing salt was the cause of some types of dieback seen in roadside trees came when experiments were performed on non-roadside trees which were artificially salted. For example, in the USA Smith and Treaster (1982) applied NaCl to the soil under 10-year-old sugar maples and found that foliar necrosis and defoliation identical to that found on roadside trees occurred, injury being greater with increasing application rate. Similarly, an unexplained disease of ponderosa pine (*Pinus ponderosa*) evident since 1954 in Denver, Colorado (Staley *et al.*, 1968) was accounted for when Spotts *et al.* (1972) were able to reproduce the symptoms of needle discoloration and defoliation in potted trees that had been treated with NaCl solution. Once again the severity of damage increased with increasing concentration of NaCl. Since that time the evidence that de-icing salt damages trees has become overwhelming with reports of damage to a wide range of amenity tree species from a broad spectrum of countries including Canada, Czechoslovakia, Denmark, East Germany, Holland, Hungary, and the Soviet Union (Hall *et al.*, 1973; Pelisek, 1983; Hvass, 1986; Suchara, 1983; Liem *et al.*, 1985; Török and Klincsek, 1978; Kydar, 1981).

Having established that salt is a significant cause of damage to roadside trees the question arose as to whether injury was as a result of excessive salinity in the soil (Ruge and Stach, 1968) or was due to salt spray thrown on to the aerial parts of trees by fast moving traffic (Hofstra and Hall, 1971). Early reports considered that damage arising from the use of de-icing salt was because of the movement of salt through soil water and into plants through their roots. However, later reports showed that salt spray whipped up by fast moving traffic also contributes to much of the damage to aerial parts of roadside plants. This latter type of damage is especially noticeable on evergreens and is most severe close to highways. Nevertheless, where strong winds carry the spray, damage may be evident up to 120 m away from the carriageway (Hofstra and Hall, 1971). An understanding of the relative impacts of these two types of damage is very important and is considered in detail under 'Symptomatology'.

The situation in Britain

Considerably more salt is used to de-ice thoroughfares in Britain than in other European countries (Table 1.1). It is surprising therefore that there are only five publications which deal directly with salt damage to trees and shrubs in Britain. Two of these deal with a single inhospitable habitat – central reservations of motorways (Colwill *et al.*, 1982; Thompson and Rutter, 1986), one deals with a single tree species (Gibbs and Burdekin, 1983), and the final two concern a single tree! (Shaw and Hodson, 1981; Shaw *et al.*, 1982).

One of the reasons for this is undoubtedly that the problem is episodic in nature due to the extreme variability of British winters from year to year. Following hard winters, during which large quantities of salt are used, damage to trees can be extensive. This is evidenced by fact that the Pathology Diagnostic and Advisory Service of the Forestry Commission confirms many cases of suspected salt injury after such winters. However, following mild winters, when little salt is applied, further damage does not occur and the problem tends to be forgotten. A further feature of the situation in this country is that damage caused by salt is often confused with symptoms caused by other stresses (e.g. drought). The end result is that, although it is acknowledged that damage to trees from de-icing salt does occur, the severity and distribution of damage are almost entirely unknown. The only significant study carried out in this country was that of Gibbs and Burdekin (1983) who demonstrated that periodic dieback of London plane (*Platanus* × *hispanica*) could be attributed largely to excessive use of de-icing salt (Figure 1.1; Plate 4), but even here no attempt was made to quantify the damage.

In order to assess the scale of the problem in Britain one must be able to diagnose salt damage accurately. To achieve this the symptoms of salt damage must first of all be clearly defined. This Chapter therefore outlines the symptoms that have been recognised from field observations and controlled experiments, the distribution of symptoms in relation to roads and within a tree, and the levels of foliar chloride and sodium ions that have been associated with visible leaf injury. Taken together, these three diagnostic tools will enable the determination of whether damage to trees is caused by de-icing salt or another agent. Owing to the lack of information from Britain most of the symptoms described are derived from observations made in the USA, Canada and mainland Europe. However, they may apply equally well to this country.

Symptomatology

The symptoms of salt damage differ somewhat for broadleaved–deciduous and evergreen species and also depend on whether damage is caused by salt in the soil environment or by salt spray. Each of these distinct categories is therefore considered separately.

Broadleaved–deciduous species

Soil salt

Leaf symptoms

Damage from salt-contaminated soil occurs most frequently in urban areas where large amounts of salt are used for de-icing roads and pavements. Trees in such situations are often planted very close to roads and are thus directly exposed to splash, runoff and ploughed snow containing considerable quantities of salt. This salt is taken up by tree roots and is subsequently transported to the shoots. Chloride tends to accumulate in the dormant twigs and buds during late winter, with concentrations peaking just prior to budburst (Hall *et al.*, 1972; Lumis *et al.*, 1976). Depending on the sensitivity of particular species and the concentration of accumulated Cl^-, buds may fail to open causing whole branches to be devoid of leaves (Hofstra *et al.*, 1979), or the buds may open but almost as soon as they do the small developing leaves wither and die, a sympton known as 'post flushing dieback' (Gibbs and Burdekin, 1983; Plate 4). These small dead leaves may remain attached to the shoots throughout the season. On branches where buds have died before or shortly after flushing, leafing out may occur later in the season from dormant or adventitious buds further down the stem (Hofstra *et al.*, 1979). This may lead to a 'tufted' appearance. Some completely leafless trees have been observed to reflush as many as 5–6 times during a single growing season (Ruge and Stach, 1968). In less severe cases buds flush, possibly up to 3–4 weeks late (Dobson, unpublished data), but leaves may not reach full maturity still being small in May (Ruge and Stach, 1968). On apparently healthy branches or trees where leaves have developed normally, leaves may begin to show marginal browning and necrosis from June onwards and may begin to wrinkle and curl (Rudolfs, 1919; Francis and Curtis, 1979; Plates 5–8). The necrosis spreads in the interveinal tissue and by August trees have an autumnal appearance (Ruge and Stach, 1968). Soon after this, premature leaf fall takes place and by the end of September trees may be fully or partially defoliated (Plate 9). All of the above symptoms may be found on a single tree, although within a tree symptoms are commonly confined to individual branches.

Dieback and death

Crown dieback (including leaf, shoot and limb death) is a common consequence of severe salt damage to trees (Plates 9, 11 and 13). The timescale on which it occurs varies greatly: it may occur very quickly leading to death of whole trees within a few months (this is especially common on young and newly planted trees), or it may involve a more gradual decline. In the latter case the amount of dieback can vary considerably from year to year so that in some years dieback is extensive, affecting whole limbs (Shaw *et al.*, 1982) whilst in others it is comparatively modest affecting only the previous year's twig growth (Sucoff *et al.*, 1976). The processes involved in dieback have received little detailed investigation but for London plane it is known that on branches where all the leaves died immediately after flushing the cortical tissues could remain green until July or August. Weak pathogens affecting the bark begin to colonise the tissue from late summer onwards (J. N. Gibbs, unpublished).

A further symptom associated with salt induced dieback of London plane and several other species in Britain is the death of tongues of bark stretching from the root collar to several feet up the trunk (Plates 10 and 12). The mechanisms for this type of injury are not known but where roots have been excavated below these areas of necrosis significant root death has often occurred (R. G. Strouts, unpublished). The symptom is similar to that caused by *Phytophthora* (see 'Damage to roots', p.12) but this fungus has not been isolated from the soil or roots of any London plane showing such stem lesions.

A useful method that has been employed to date the onset of dieback is ring-width analysis. Eckstein *et al.* (1978) showed that significant reductions in radial increment of horse chestnut 0.5 m from the road edge in Freiburg, Germany, occurred after salt was first used in the mid 1960s. Between 1970–1973 growth was so severely retarded that increments were almost non-detectable and by 1974 the trees were dead. Control trees showed normal growth during this period. Petersen and Eckstein (1988) found a similar sequence of decline following the onset of winter road salting in Hamburg.

Salt spray

Damage from salt spray may be found beside any salted road with fast moving traffic but is often most noticeable along motorways and trunk roads. It is uncommon for spray damage to be seen in towns and cities because of slow traffic movement. Although deciduous trees have no leaves in winter they may still be affected by salt spray. This is because the dormant twigs intercept the salt which may then reach living tissue by entering the twigs at leaf scars (Sucoff, 1975). This results in the death of dormant buds and may cause dieback of the previous years twig growth. The portion of the stem between the buds may also show dead spots and examination of the cambial tissue may reveal almost total browning (Sucoff, 1975). Due to the death of apical buds, lateral buds on wood more than one year old may be released which can lead to a 'witches broom' appearance. If buds are not killed, leafing out in spring may be delayed by up to 3 weeks (Sucoff, 1975). In contrast to damage from salt in the soil, marginal necrosis rarely occurs. However, damage to newly emerging foliage may occur in spring if there are late frosts necessitating road salting. In contrast to salt taken up by the roots, salt spray rarely causes tree death outright, but annually recurring damage tends to keep crowns narrow, stems thin and plants short.

Evergreens (pine and spruce)

Symptomatology of salt damage for pines and spruce is fairly well documented in the North American literature. These reports tend to show that symptoms become evident in late February or early March following the spring thaw (Sucoff *et al.*, 1975). Lumis *et al.* (1976) reported that salt damage to vegetation increased through the spring probably due to rising temperatures. Hall *et al.* (1972) found that 4-year-old *Pinus strobus* failed to show injury symptoms as long as they were maintained at air temperatures below 1.5°C. However, symptoms became apparent 2 days after trees were transferred to an air temperature of 15°C. In Britain, where temperatures do not remain below freezing for long, injury may develop fairly rapidly after salting episodes.

Soil salt

The symptoms associated with soil-salt toxicity have not been investigated in detail but are generally similar to those associated with damage from salt spray. However, the principal symptoms which indicate soil salt damage rather than salt spray damage appear to be the failure of buds to flush (Sury and Flückiger, 1983) and the browning of needles the summer that they emerge from the bud (Sucoff, 1975). Other factors that suggest damage from salt in the soil are when needles in the upper crown show proportionately greater damage than those lower down, and when needles sheltered from spray show as much damage as those exposed to it (Sucoff, 1975).

Salt spray

Damage from salt spray first becomes apparent on one-year-old needles as 'tipburn' (Spotts *et al.*, 1972; Plates 14 and 15). The tips of the needles first turn yellow, then bronze and subsequently become brown and necrotic. There is generally a clear demarcation between the basal green and the terminal brown tissue (Hofstra and Hall, 1971). Pyykkö (1977) has shown that, for Scots pine (*Pinus sylvestris*), salt crystals are plentiful in the intercellular spaces at the boundary between healthy and necrotic tissue. Just before browning yellow bands sometimes appear across the needles which may exude resin (Staley *et al.*, 1968; Spotts *et al.*, 1972) and needles may become flecked with tiny bleached spots which often disappear later in the season (Plate 15). These flecks help distinguish salt damage from other types of needle browning (Sucoff *et al.*, 1975). Through spring and summer necrosis progresses towards the base of the needle, affecting up to 75% of the needle in severe cases (Sucoff *et al.*, 1975). On older needles, browned in previous years, necrosis continues towards the base and 2- or 3-year-old needles that are more than half brown tend to fall off. Damage generally starts at the tips of branches and progresses back into the crown (Hofstra *et al.*, 1979).

Buds of pines are rarely affected by salt spray and flush normally in the spring with new leaves remaining green and healthy throughout their first year. This tends to mask the older brown needles giving the appearance of recovery (Hall *et al.*, 1972), but where shedding of older needles is considerable trees have noticeably thinner crowns (Sucoff *et al.*, 1975).

Other evergreens

The situation with other conifers is broadly similar to that of pine and spruce (Plate 16). Foster and Maun (1978) showed that salt spray caused yellowing and necrosis of shoot tips in eastern white cedar (*Thuja occidentalis*). Necrosis extended basipetally and the demarcation between the necrotic and healthy tissue was sharp. Symptoms were similar for soil applied

Plate 4. *Post flushing dieback on London plane (*Platanus × hispanica*), Victoria Embankment, London. (J. N. Gibbs)*

Plate 5. *Left: marginal and interveinal browning of London plane leaf caused by soil salt. Right: healthy London plane leaf. (M. Levy)*

Plate 6. *Yellowing and browning of small-leaved lime (*Tilia cordata*) in a controlled experiment where salt was added to the soil. (M. C. Dobson)*

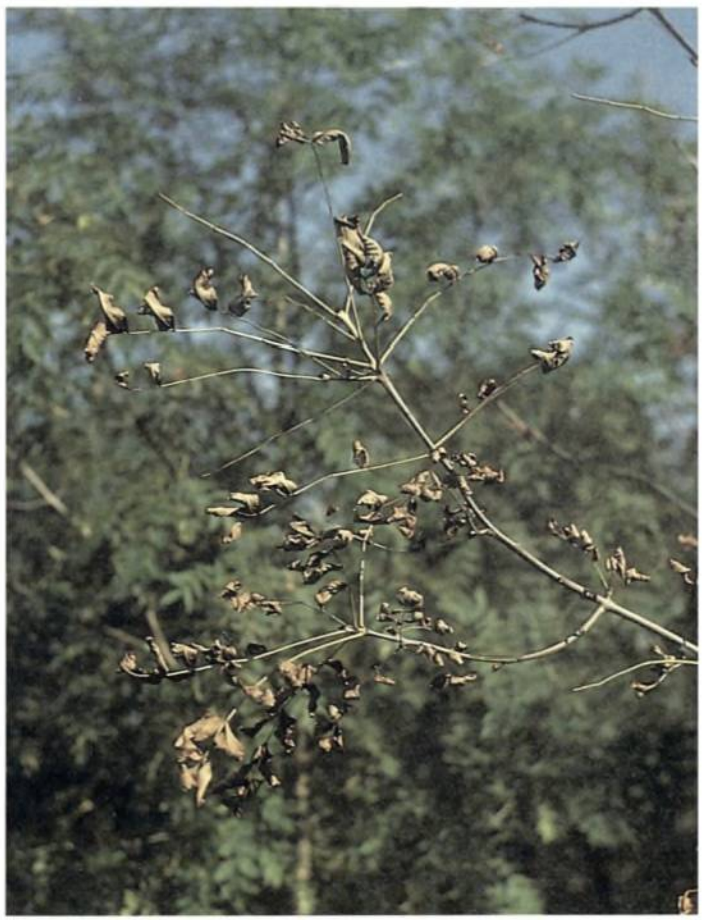

Plate 7. *Leaf browning and defoliation of ash (*Fraxinus excelsior*) caused by soil salt. (M. C. Dobson)*

Plate 8. *Marginal necrosis on beech (*Fagus sylvatica*) leaves caused by salt contaminated soil. (M. C. Dobson)*

Plate 9. *Crown dieback on Swedish whitebeam (*Sorbus intermedia*), Wakefield. (J. N. Gibbs)*

Plate 10. *Stem lesion extending several metres up the trunk on London plane resulting from root absorption of salt. Trunk damage was accompanied by almost complete defoliation. (D. Thorogood)*

Plate 11. *Crown dieback of lime. A pile of de-icing salt was placed beneath the crown of the tree in winter (the remains can still be seen) and resulted in the eventual death of the tree and surrounding vegetation. (J. N. Gibbs)*

Plate 12. *Damaged London plane tree adjacent to a salt storage bin. (D. Patch)*

Plate 13. *Death of mature trees next to a salt storage site. (D. K. Barrett)*

Plate 14. *Salt spray damage to coast redwood (*Sequoia sempervirens*) in Hampshire. (M. C. Dobson)*

Plate 15. *Susceptibility to salt spray. Left: relatively tolerant Corsican pine (*Pinus nigra *var.* maritima*). Right: sensitive lodgepole pine (*P. contorta*). (39859)*

Plate 16. *Salt spray damage on cypress shoot (left). (39278)*

Plate 17. *Marginal necrosis of bay laurel (*Laurus nobilis*) leaf (left) caused by salt spray. (39276)*

salt but yellowing also occurred at the bases of secondary and tertiary branches and progressed acropetally and basipetally. Bernstein *et al.* (1972) similarly showed that soil salting could cause necrotic shoot tips and basal shoot necrosis for *Thuja orientalis* and *Juniperus chinensis*. A further symptom for *J. chinensis* was appression of leaf scales.

Broadleaved-evergreens may show a variety of symptoms (e.g. Plate 17). Dirr (1975) showed that salt caused marginal necrosis in English ivy (*Hedera helix*). However some species may show bronzing rather than necrosis of leaf margins or tips (e.g. Chinese privet, *Ligustrum lucidum*) and others may show bronzing in addition to scorch (e.g. Chinese shrubby holly, *Ilex cornuta*; Bernstein *et al.*, 1972). Other species may show milder symptoms such as very slight marginal necrosis and drop their leaves before stronger symptoms develop. An example of this is pittosporum (*Pittosporum tobira*) which showed severe leaf drop in response to soil-salt leaving only rosettes of leaves at the end of bare stems (Bernstein *et al.*, 1972).

Microscopic symptoms and changes in growth

Internal leaf structure may change as a result of salt stress. Succulence of leaves can increase slightly for leaves exposed to NaCl (Longstreth and Noble, 1979) due to an increase in the number of spongy cell layers in the mesophyll and because of increased length of palisade cells. Increase in the size of cells is thought to be due to the greater amount of salt inside the cell which produces a greater osmotic differential between the plant and the external medium such that turgor is increased (Jennings, 1976). Larger cells are therefore a consequence of the maintenance of this increased turgor.

Damage to leaves of trees exposed to salt may also include disrupted stomata, collapsed cell walls, disorganised or disintegrated protoplasts, coarsely granular cytoplasm, disintegrated chloroplasts, disintegrated nuclei and disorganised phloem (Kutscha *et al.*, 1977). Both soil and foliar applications of salt can produce the above symptoms although leaves tend to be somewhat less damaged by soil-applied than foliar-applied salt. Examination of NaCl-sprayed pines using SEM (Krause, 1982) also revealed changes in surface structure. Needles sprayed with salt solution lacked downy epicuticular wax and had rows of flaccid subsidiary cells.

Salt may also affect wood structure. Eckstein *et al.* (1976) found that besides reducing cambial activity salt increased the proportion of vessels and decreased the percentage of wood rays and fibres of salt-stressed horse chestnut (*Aesculus hippocastanum*). Damaged trees also contained an increased proportion of parenchyma at the expense of vessels which contributed to water stress effects and decreased mechanical strength (Petersen and Eckstein, 1988). Salt caused xylem vessels to become smaller in diameter, circular rather than oval and the number of vesels per unit area to increase. These symptoms are similar to those found in drought-stressed trees and may reflect an adaptation to higher suction force as a result of salt accumulation in the soil. Salt stressed trees exhibit other features which are associated with drought such as a decrease in water content of leaves (Foster and Maun, 1978; Simini and Leone, 1986a), stomatal closure (Petersen and Eckstein, 1988) and more negative water potentials (Leonardi and Flückiger, 1985). West (1978a) has also shown that salinity stress, of itself, can reduce water uptake in apple trees (*Malus sylvestris*) by up to 50%.

Decreased growth may result from the loss of photosynthetic capacity (Longstreth and Nobel, 1979; Bongi and Loreto, 1989) and from loss of photosynthetic area due to the failure of leaf buds to expand, because of leaf necrosis, and through premature defoliation. De-icing salt may decrease growth even in the absence of visible injury. Such 'invisible' damage results from changes in physiology leading to growth reductions and changes in plant structure. For example, Semoradova and Materna (1982) found that annual height increment of several tree species was reduced by salt application, the magnitude of this decrease being linearly related to dose. Shortle *et al.* (1972) discovered that in sugar maples affected by de-icing salt shoot growth was inversely correlated with the amount of chloride accumulated in the leaves. A similar relationship has been established for *Robinia pseudoacacia* in several cities in the south of England in the absence of any visible leaf symptoms (Colderick and Hodge, 1991). Bernstein *et al.* (1972) and Francois and Clark (1978) independently found, after examining the response of several shrub and tree species to different NaCl concentrations, that, in general, leaves were only visibly damaged at levels that suppressed growth by 50% or more. Furthermore, although in sugar maple visible injury is unlikely to occur until foliar chloride concentrations exceed 0.4% of the dry weight, significant decline in vigour may be expected once foliar concentrations reach 0.15% (Rubens, 1978). In addition to reductions in shoot growth, terminal bud weight, leaf length, fresh and dry weights of leaves, stems and roots (Hall *et al.*, 1972; Simini and Leone, 1986b), and for fruiting trees (e.g. *Prunus persica*; Northover, 1987), weight of fruit may also be reduced.

Damage to roots

Direct damage

Guttay (1976) examined the root systems of 44 roadside sugar maples in Connecticut and found that salt damaged trees had very few surface roots. Healthy maples usually have 80% of their total root volume in the upper 20 cm of soil (Morrow, 1950), however, Guttay had difficulty in finding any viable roots at all in the upper 30 cm of soil indicating a significant loss in root volume. In addition to this there were significantly fewer endomycorrhizae in severely damaged trees than in trees rated as undamaged. Sodium and chloride ion concentrations in the roots were significantly higher in the moderately and severely damaged trees than in the undamaged trees. Guttay (1976) concluded that damage to sugar maple was probably caused by a progressive destruction of the root and endomycorrhizal system from the soil surface downwards with continued annual salt applications. He reasoned that top dieback was caused by the inability of the diminishing root system to sustain the top growth. Krapfenbauer *et al.* (1974) similarly found that high salt concentrations in the soil led to direct damage to the root systems of Norway maple (*Acer platanoides*) in Vienna. Wester and Cohen (1968) found that after an exceptionally severe winter (1966–67) in Washington DC heavy salt applications had plasmolysed fine root tissue, thus preventing water absorption which in turn damaged foliage and retarded shoot development.

Indirect damage

Low concentrations of salt give rise to severe indirect damage to roots through deterioration of soil structure and loss of mineral nutrients. Sodium tends to displace other nutritionally more important ions from cation exchange sites thus reducing availability of these ions to plants and causing deflocculation of soil particles and therefore soil compaction (see Chapter 4 for a fuller discussion).

High salt concentrations in the soil may also render trees more susceptible to attack from other agents with the result that additional symptoms appear. For example, in their study of roadside trees in New Hampshire Lacasse and Rich (1964) found that 'bleeding canker' caused by *Phytophthora cactorum* was frequently seen on injured sugar maples. Although no cause-effect relationship was established this ties in with the findings of Blaker and MacDonald (1985; 1986) who demonstrated that root rot of citrus caused by *Phytophthora parasitica* increased with soil salinity. Up to 30% of root length was decayed in saline conditions but only 10% in non-saline. Total root growth and production of new roots was greatly inhibited by saline soils.

Practical diagnosis of salt damage

Some of the symptoms described above can be caused by stresses other than salt. For example, marginal necrosis of leaves can be caused by drought and desiccation by strong winds as well as by salt toxicity. It is therefore only after thorough evaluation of the symptoms and consideration of all the environmental conditions at a particular site that de-icing salt can be singled out as the most probable cause of damage.

Location of the injured tree and distribution of damage within a tree are valuable guides when assessing the possible contribution of salt to damage of roadside trees. The following are general injury patterns that have been identified (Lumis *et al.*, 1975; Dirr, 1976; Hofstra *et al.*, 1979) and may apply equally to salted paths and pavements as to roads.

1. Trees close to roads are generally the worst affected. Damage is most severe within 5 m of the road but there is frequently a distinct injury gradient with distance; damage being minimal at about 30 m from the road. (However, where roots penetrate drains carrying salty runoff damage may occur at a considerable distance from roads.)
2. Trees on the downhill side of a road suffer more damage than those on the uphill side.
3. Trees planted in depressions or with depressions around their base (e.g. where planting soil has settled) suffer more damage than trees in raised planting sites.

On high-speed roads (e.g. motorways), where salt spray rather than runoff is the major cause of injury, the following distribution of damage can be seen.

4. Trees on the downwind side of the carriageway show greatest injury.
5. Injury is greatest on the side of the tree facing the road. (Trees are often mis-shapen and one-sided in appearance due to the death of buds and branches facing the road.)
6. Trees sheltered from spray, e.g. by fencing between trees and road, lack injury symptoms.
7. Injury is greatest on the lowest branches. Branches above the spray-drift zone are not injured or are less injured.
8. Flowers may only come out on the side of the tree facing away from the road. This is because flower buds are more sensitive to salt spray than leaf buds.
9. Where deep snow lies for significant periods of time (which rarely occurs in most parts of Britain), injury does not occur beneath the snow line.

If the type and distribution of symptoms indicate salt damage, diagnosis may be confirmed by analysing damaged and, for comparison, undamaged foliage for sodium and chloride content. Although analysis of foliage for sodium is useful, foliar chloride concentrations are better correlated with damage. There appears to be a threshold concentration above which toxicity symptoms are expressed and this varies from species to species. Nevertheless, as a general rule, injury symptoms tend to occur once the chloride content of leaves exceeds about 1% of the oven dry weight for broadleaves, and about 0.5% for conifers. The available information on levels of sodium and chloride associated with leaf injury was summarised by Sucoff in 1975. He listed the levels of sodium and chloride causing damage to 19 and 35 woody species respectively. Much further work has been published since then and this is summarised in Tables 1.2 and 1.3 which detail the levels of chloride (130 species) and sodium (47 species) in leaves of woody plants with and without leaf salt-toxicity symptoms.

Conclusions

It is beyond doubt that salt used for de-icing thoroughfares can cause serious damage to trees and shrubs. Considerable progress has been made in the recognition of salt damage symptoms since the first investigations in the 1950s so that general patterns of injury are now fairly well understood. There is also a substantial body of data in the literature concerning the concentrations of sodium and chloride associated with foliar injury (Tables 1.2 and 1.3). These data are an extremely valuable resource for aiding in the confirmation of suspected cases of salt damage.

Although it is known that salt damage to trees is widespread in Britain following cold winters, the severity and distribution of damage symptoms are almost entirely unknown. It is vitally important therefore that the scale of damage is assessed by means of comprehensive surveys.

Table 1.2 Concentrations of chloride in the leaves of 130 woody species, with and without leaf salt-toxicity symptoms. Data summarised from the literature.

	Leaf Cl^- (% oven dry weight)				
Species	*No symptoms*	*Symptoms in field observation*	*Symptoms in controlled application*	*Month of observation*	*Author*
Abies alba	<0.1	–	0.7-2.5	–	Sury and Flückiger (1983)
Abies fraseri	0.27-0.51	–	–	Sep/Nov	Robarge *et al.* (1989)
Acer campestre	<0.7	–	>0.7	Aug/Sep	Burg (1989)
Acer negundo	0.07	–	–	–	Edwards *et al.* (1981)
	<0.06	1.37-1.39	–	Jan–Apr	Lumis *et al.* (1976)
	0.26-0.84	0.18-1.28	–	Aug	Sucoff (1975)
Acer platanoides	<0.7	–	0.7-2.6	Aug/Sep	Burg (1989)
	0.44	–	2.65	–	Dirr (1978)
	0.12-0.21	0.82-1.65	–	–	Krapfenbauer (1976)
	0.19-0.21	1.37	–	Jun	Kydar (1981)
	0.43	1.68	–	Jun/Jul/Aug	Leh (1973)
	<0.06	0.66-0.92	–	Jan–Apr	Lumis *et al.* (1976)
	<0.2	0.2-2.2	–	Jun	Walton (1969)
	0.01-1.0	–	1.8-3.7	–	Zulauf (1965)
Acer pseudoplatanus	0.26-0.28	–	0.6-2.05	–	Braun *et al.* (1978)
	<0.6	–	0.9-3.5	Aug/Sep	Burg (1989)
	–	2.39	–	Jun/Jul/Aug	Leh (1973)
	0.069	–	0.39-0.62	–	Semoradova and Materna (1982)
Acer rubrum	0.36	1.01	–	–	Shortle and Rich (1970)
Acer saccharinum	<1.0	–	1.0-1.9	Aug/Sep	Burg (1989)
	0.03-0.19	0.16-1.18	–	Apr/Jun/Sep	Hanes *et al.* (1970b)
	0.11-0.6	0.08-1.34	–	Aug	Sucoff (1975)
Acer saccharum	0.02-0.14	0.04-0.93	0.05-1.40	Aug	Button and Peaslee (1970)
	–	0.54-0.76	–	Aug	Hall *et al.* (1973)
	0.02-0.06	–	0.13-0.25	Aug	Hanes *et al.* (1970c)
	0.05-0.29	–	3.64	Aug	Holmes (1961)
	0.05-0.61	0.17-1.01	–	Jul	Holmes and Baker (1966)
	0.02-0.09	0.04-1.30	–	Aug	Kotheimer (1967)
	<0.06	0.71-0.80	–	Jan–Apr	Lumis *et al.* (1976)
	0.24	0.84	–	–	Shortle and Rich (1970)
	0.04-0.95	0.08-1.54	–	Aug	Sucoff (1975)
Aesculus × *carnea*	<1.2	–	1.4-4.7	Aug/Sep	Burg (1989)
Aesculus hippocastanum	0.036-0.210	1.10-2.85	–	–	Blum (1974)
	0.118-0.122	–	0.382-2.616	–	Braun *et al.* (1978)
	<0.7	–	0.9-3.2	Aug/Sep	Burg (1989)
	–	0.8-1.36	–	Aug/Sep	Fuhrer and Erismann (1980)
	0.13-0.551	0.995	–	Jun/Jul/Aug	Leh (1973)
	0.13-0.83	0.136-2.66	–	Jun/Jul/Aug	Leh (1973)
	0.75	1.25	–	Jun/Jul/Aug	Leh (1973)
Ailanthus altissima	–	–	2.0-3.0	Aug/Sep	Burg (1989)
	0.153	–	0.33-1.06	–	Semoradova and Materna (1982)
Alnus glutinosa	<0.6	–	0.6-2.0	Aug/Sep	Burg (1989)
Alnus incana	<0.5	–	0.5-1.4	Aug/Sep	Burg (1989)
Alnus rugosa	0.54	0.91	–	–	Shortle and Rich (1970)
Alnus × *spaethii*	<1.4	–	1.2-1.8	Aug/Sep	Burg (1989)
Betula alleghaniensis	0.10-0.78	–	–	Aug/Sep	Shortle and Rich (1970)

Table 1.2 continued.

	Leaf Cl⁻ (% oven dry weight)				
Species	*No symptoms*	*Symptoms in field observation*	*Symptoms in controlled application*	*Month of observation*	*Author*
Betula jacqemontii	<0.7	–	1.0-1.2	Aug/Sep	Burg (1989)
Betula lenta	0.09-0.84	–	–	Aug/Sep	Shortle and Rich (1970)
Betula papyrifera	0.12	–	0.42-0.56	Aug	Hanes *et al.* (1970c)
	0.01-1.15	–	–	Aug/Sep	Shortle and Rich (1970)
Betula pendula	<0.3	–	0.4-1.6	Aug/Sep	Burg (1989)
	0.05	–	–	–	Edwards *et al.* (1981)
Betula populifolia	0.05-0.27	–	–	–	Shortle and Rich (1970)
Caragana arborescens	0.23	–	–	–	Edwards *et al.* (1981)
Carpinus betulus	<0.5	–	>0.5	Aug/Sep	Burg (1989)
	0.66	1.81	–	Sep	FC records (1982)
	0.8-1.6	2.0-3.0	–	–	FC records (1985)
Carpinus caroliniana	0.34	0.94	–	Aug/Sep	Shortle and Rich (1970)
Carya ovata	0.27	1.27	–	Aug/Sep	Shortle and Rich (1970)
Celtis occidentalis	0.07-1.45	0.01-2.22	–	–	Sucoff (1975)
Cercis canadensis	0.60	–	3.6-11.6	Apr	Dirr (1976)
Chamaecyparis lawsoniana	0.69	2.36	–	Oct	FC records (1985)
Chamaedaphne calyculata	–	0.11-0.19	–	Jul/Aug	Foss (1971)
Cornus florida	–	–	0.28-0.83	–	Francis and Curtis (1979)
Cornus stolonifera	0.03	–	–	–	Edwards *et al.* (1981)
	<0.06	1.20-2.00	–	Jan–Apr	Lumis *et al.* (1976)
Corylus colurna	<0.6	–	0.6-2.5	Aug/Sep	Burg (1989)
Crataegus monogyna	<0.3	–	0.3-1.0	Aug/Sep	Burg (1989)
Crataegus oxyacantha	<0.1	–	0.1-0.6	Aug/Sep	Burg (1989)
Elaeagnus angustifolia	0.40-0.70	–	–	Apr	Dirr (1978)
	0.04	–	–	–	Edwards *et al.* (1981)
	0.005	–	0.007	–	Semoradova and Materna (1982)
Elaeagnus umbellata	0.32	–	2.63	Apr	Dirr (1978)
Fagus grandifolia	<0.06	0.39-0.83	–	Jan–Apr	Lumis *et al.* (1976)
Fagus sylvatica	<0.5	–	0.5-3.2	Aug/Sep	Burg (1989)
	0.95	2.30	–	Jun/Jul/Aug	Leh (1973)
Forsythia × intermedia	0.2-0.8	–	–	Aug	Hanes *et al.* (1970d)
Fraxinus americana	0.1	0.4	–	Aug/Sep	Shortle and Rich (1970)
Fraxinus excelsior	<0.4	–	0.4-3.0	Aug/Sep	Burg (1989)
	0.063	–	0.26-0.39	–	Semoradova and Materna (1982)
Fraxinus pennsylvanica	0.07	–	–	–	Edwards *et al.* (1981)
	0.04-0.34	0.04-2.55	–	Aug	Sucoff (1975)
Ginkgo biloba	<1.2	–	1.8-3.0	Aug/Sep	Burg (1989)
Gleditsia triacanthos	<0.7	–	1.0-6.6	Aug/Sep	Burg (1989)
	0.04-0.18	–	–	Aug	Hanes *et al.* (1970c)
	–	0.08-0.16	–	Aug	Sucoff (1975)
Gleditsia triacanthos cv Inermis	<0.3	–	2.6	Aug/Sep	Burg (1989)
Hedera helix	0.4	–	1.4-1.9	Apr	Dirr (1976)
Juniperus chinensis	0.08-0.15	0.16-0.18	–	Aug	Hanes *et al.* (1970e)
Juniperus horizontalis	0.045	0.16-0.18	–	Jun	FC records (1984)
	0.05	–	0.2	Aug	Hanes *et al.* (1970e)
Juniperus virginiana	0.06-0.09	–	–	Aug/Sep	Shortle and Rich (1970)

Table 1.2 continued.

	Leaf Cl^- (% oven dry weight)				
Species	*No symptoms*	*Symptoms in field observation*	*Symptoms in controlled application*	*Month of observation*	*Author*
Larix decidua	0.044	–	0.19-0.67	–	Semoradova and Materna (1982)
Ligustrum amurense	<0.06	0.58-0.77	–	Jan–Apr	Lumis *et al.* (1976)
Ligustrum vulgare	0.1-0.6	1.0-1.6	–	Aug	Hanes *et al.* (1970d)
Liquidambar styraciflua	<0.3	–	>0.4	Aug/Sep	Burg (1989)
Liriodendron tulipifera	<1.1	–	1.3-2.6	Aug/Sep	Burg (1989)
Lonicera tatarica	0.37	–	–	–	Edwards *et al.* (1981)
	0.1-0.5	0.8-0.9	0.7-0.9	Aug	Hanes *et al.* (1970d)
Malus sp.	–	0.08	–	Aug	Sucoff (1975)
Malus sylvestris	<0.5	–	0.6-1.0	Aug/Sep	Burg (1989)
	–	0.30-1.31	–	May	Hofstra and Lumis (1975)
	<0.06	0.65-0.85	–	Jan–Apr	Lumis *et al.* (1976)
Picea abies	<0.15	0.2-0.4	–	–	Dragsted (1973)
	0.02-0.09	0.23	–	Feb	FC records (1986)
	0.46	–	0.28	Aug	Hanes *et al.* (1970e)
	0.10-0.16	0.03-0.32	–	Apr	Hutchinson *et al.* (1967)
	0.019	–	0.12-0.26	–	Semoradova and Materna (1982)
Picea glauca	0.05	–	–	–	Edwards *et al.* (1981)
	0.07-0.08	0.19-0.26	–	Aug	Sucoff (1975)
Picea mariana	–	0.03-1.17	–	Jul/Aug	Foss (1971)
Picea pungens	0.03	1.43	–	–	Edwards *et al.* (1981)
	0.024-0.36	–	–	–	Semoradova and Materna (1982)
	–	0.08-0.56	–	Aug	Sucoff (1975)
Picea rubens	0.44-0.63	–	–	Sep/Nov	Robarge *et al.* (1989)
Pinus aristata	0.04	–	4.06	Mar/Apr	Townsend (1983)
Pinus cembra	0.08	–	2.18	Mar/Apr	Townsend (1983)
Pinus contorta	0.039	0.67	–	–	Edwards *et al.* (1981)
Pinus mugo	0.07	0.58-1.12	–	May	Hofstra and Hall (1971)
	0.015-0.20	–	–	–	Semoradova and Materna (1982)
Pinus nigra	0.10-0.11	0.68-0.80	–	May	Hofstra and Hall (1971)
	<0.06	0.56-0.74	–	Jan–Apr	Lumis *et al.* (1976)
	0.1-0.25	0.09-0.59	–	Aug	Sucoff (1975)
Pinus parviflora	0.13	–	2.18	Mar/Apr	Townsend (1983)
Pinus peuce	0.03	–	4.84	Mar/Apr	Townsend (1983)
Pinus ponderosa	0.04	–	1.36-2.18	Jun	Bedunah and Trlica (1979)
	0.06	–	2.3-3.3	–	Spotts *et al.* (1972)
	0.17	–	1.68	–	Scharpf and Srago (1974)
Pinus resinosa	0.03	–	–	–	Edwards *et al.* (1981)
	0.2-0.3	0.3-0.7	–	May	Hofstra and Hall (1971)
	0.09	0.004-0.41	–	Apr	Hutchinson *et al.* (1967)
	0.06	1.08	–	–	Shortle and Rich (1970)
	0.03-0.49	0.1-1.29	–	Aug	Sucoff (1975)
	0.14-0.39	0.5-0.9	–	Apr/May/Jun	Sucoff *et al.* (1975)
Pinus ayacahuite (var. *brachyptera*)	0.13	–	2.44	Mar/Apr	Townsend (1983)

Table 1.2 continued.

	Leaf Cl⁻ (% oven dry weight)				
Species	*No symptoms*	*Symptoms in field observation*	*Symptoms in controlled application*	*Month of observation*	*Author*
Pinus strobus	–	0.33-0.56	–	Jul/Aug	Foss (1971)
	0.03-0.50	–	0.40-0.50	Aug	Hanes *et al.* (1970e)
	0.03-0.07	1.0	–	May	Hofstra and Hall (1971)
	<0.06	1.0-1.25	–	Jan–Apr	Lumis *et al.* (1976)
	0.24	0.58	–	–	Shortle and Rich (1970)
	0.03	–	3.67	Mar/Apr	Townsend (1983)
Pinus sylvestris	0.05	–	–	–	Edwards *et al.* (1981)
	0.024	0.021	–	Feb	Garber (1964)
	–	0.17-2.06	–	May	Hofstra and Hall (1971)
	–	0.20	–	Aug	Sucoff (1975)
Pinus thunbergii	0.03	–	1.34	Mar/Apr	Townsend (1983)
Platanus × *hispanica*	<1.5	–	1.1-4.2	Aug/Sep	Burg (1989)
	0.28-0.8	1.10-2.05	–	–	Gibbs and Burdekin (1983)
	0.22-0.48	1.08-1.47	–	Jun/Jul/Aug	Leh (1973)
Populus sp.	1.50	3.00	–	Jun/Jul/Aug	Leh (1973)
Populus balsamifera	0.08	–	–	–	Edwards *et al.* (1981)
Populus × *canadensis*	<0.7	–	1.0-3.9	Aug/Sep	Burg (1989)
Populus × *canescens*	<0.8	–	0.8-1.7	Aug/Sep	Burg (1989)
Populus grandidentata	0.10	0.66	–	–	Shortle and Rich (1970)
Populus nigra	<0.6	–	>0.7	Aug/Sep	Burg (1989)
	0.42-0.9	0.88-3.50	–	Jul	FC records (1982)
Populus tremula	<0.7	–	1.0-1.4	Aug/Sep	Burg (1989)
Populus tremuloides	0.31	–	–	–	Edwards *et al.* (1981)
	0.12-0.78	–	–	Aug/Sep	Shortle and Rich (1970)
Prunus avium	<0.3	–	>0.3	Aug/Sep	Burg (1989)
Prunus besseyi	0.23	–	4.35	Apr	Dirr (1978)
Prunus cerasifera	<0.5	–	0.5-0.9	Aug/Sep	Burg (1989)
Prunus cerasus	<0.4	–	>0.3	Aug/Sep	Burg (1989)
Prunus domestica	<0.7	–	0.7-1.5	Aug/Sep	Burg (1989)
Prunus padus	<0.1	–	0.5-2.9	Aug/Sep	Burg (1989)
Prunus persica	0.09	0.69-0.9	–	–	Northover (1987)
Prunus serotina	0.02	0.09	–	–	Shortle and Rich (1970)
Prunus tomentosa	0.30	–	2.72	Apr	Dirr (1978)
Prunus virginiana	0.31	–	–	–	Edwards *et al.* (1981)
Pseudotsuga menzeisii	0.17	0.21-0.27	–	Jul	FC records (1988)
	0.58	–	–	Aug	Sucoff (1975)
Pterocarya fraxinifolia	<1.1	–	1.1-1.4	Aug/Sep	Burg (1989)
Pyracantha coccinea	0.30	–	1.7-3.7	Apr	Dirr (1976)
Pyrus calleryana cv Chanticleer	0.02-0.05	–	0.10-0.15	Aug/Sep	Burg (1989)
Pyrus communis	0.03-0.08	–	0.15-0.25	Aug/Sep	Burg (1989)
Quercus alba	0.06-0.14	–	–	Aug/Sep	Shortle and Rich (1970)
Quercus macrocarpa	0.03	–	–	–	Edwards *et al.* (1981)
Quercus robur	0.019	–	0.045-0.07	–	Semoradova and Materna (1982)
Quercus rubra	0.007-0.04	–	–	–	Semoradova and Materna (1982)
	0.02	–	–	Aug/Sep	Shortle and Rich (1970)
Rhamnus sp.	–	0.42-1.38	–	Aug	Sucoff (1975)

Table 1.2 continued.

	Leaf Cl^- (% oven dry weight)				
Species	*No symptoms*	*Symptoms in field observation*	*Symptoms in controlled application*	*Month of observation*	*Author*
Rhus glabra	0.23	–	3.29	Apr	Dirr (1978)
	0.06-0.88	0.10-2.04	–	Aug	Sucoff (1975)
Robinia pseudoacacia	<1.0	–	1.4-3.5	Aug/Sep	Burg (1989)
	0.19-0.26	–	–	Jun/Jul/Aug	Leh (1973)
	0.049-0.23	–	–	–	Semoradova and Materna (1982)
	0.09-0.32	–	–	Aug/Sep	Shortle and Rich (1970)
Rosa rugosa	0.11-1.04	–	–	Apr	Dirr (1978)
Salix alba	<0.5	–	0.5-1.2	Aug/Sep	Burg (1989)
	<0.06	2.04-2.10	–	Jan–Apr	Lumis *et al.* (1976)
Salix viminalis	<0.2	–	0.5-0.8	Aug/Sep	Burg (1989)
Sophora japonica	<0.2	–	2.0-3.7	Aug/Sep	Burg (1989)
Sorbus aria	0.35-1.0	–	0.8-2.7	Aug/Sep	Burg (1989)
Sorbus aucuparia	<1.0	–	1.0-2.7	Aug/Sep	Burg (1989)
Sorbus intermedia	<1.0	–	1.0-1.3	Aug/Sep	Burg (1989)
Spiraea vanhouttei	0.20	–	1.0-1.7	Aug	Hanes *et al.* (1970d)
Syringa vulgaris	<0.06	0.61-0.70	–	Jan–Apr	Lumis *et al.* (1976)
	0.28-0.43	0.81-0.85	–	Aug	Sucoff (1975)
Thuja occidentalis	<0.3	–	>0.3	–	Foster and Maun (1978)
	<0.29	0.29-2.0	–	May	Hofstra and Hall (1971)
	–	0.39-0.74	–	–	Hofstra *et al.* (1979)
	0.33	0.13	–	Apr	Hutchinson *et al.* (1967)
	<0.06	1.42-1.98	–	Jan–Apr	Lumis *et al.* (1976)
Tilia americana	<0.2	–	0.6-0.9	Aug/Sep	Burg (1989)
	0.18	0.90	–	–	Shortle and Rich (1970)
	0.09-0.99	0.32-1.32	–	Aug	Sucoff (1975)
Tilia cordata	<0.7	–	0.7-2.6	Aug/Sep	Burg (1989)
	0.43	1.37	–	Jun	Kydar (1981)
	0.27-0.67	1.14-3.25	–	Jun/Jul/Aug	Leh (1973)
	0.50	1.65	–	Jun/Jul/Aug	Leh (1973)
	0.29-0.35	1.6-2.18	–	Jun/Jul/Aug	Leh (1975)
Tilia × *euchlora*	<1.0	–	1.0-4.4	Aug/Sep	Burg (1989)
Tilia × *europaea*	<0.6	–	0.6-2.8	Aug/Sep	Burg (1989)
	0.29	1.83-2.43	–	Jun/Jul/Aug	Leh (1973)
Tilia platyphyllos	<0.8	–	0.8-1.7	Aug/Sep	Burg (1989)
Tilia tomentosa	<0.8	–	0.8-3.5	Aug/Sep	Burg (1989)
	0.75	2.60	–	Jun/Jul/Aug	Leh (1973)
Tremula vulgaris	0.051	–	0.20-0.39	–	Semoradova and Materna (1982)
Tsuga canadensis	–	0.01-0.25	–	Apr	Hutchinson *et al.* (1967)
	0.015-0.086	0.06-0.14	–	Jul	Langille (1976)
	0.50	0.68	–	–	Shortle and Rich (1970)
Ulmus americana	0.14	–	–	–	Edwards *et al.* (1981)
	–	0.60	–	Aug/Sep	Hanes *et al.* (1970b)
	0.38	1.13	–	–	Shortle and Rich (1970)
	<0.14	0.38-2.21	–	Aug	Sucoff (1975)
Ulmus glabra	<0.9	–	1.0-2.8	Aug/Sep	Burg (1989)
Ulmus × *hollandica*	<0.7	–	0.7-3.5	Aug/Sep	Burg (1989)
Ulmus pumila	0.24	–	–	–	Edwards *et al.* (1981)
Viburnum × *burkwoodii*	0.30	–	0.9-2.2	Apr	Dirr (1976)

Table 1.3 Concentrations of sodium in the leaves of 47 woody species, with and without leaf salt-toxicity symptoms. Data summarised from the literature.

	Leaf Na^+ (% oven dry weight)				
Species	*No symptoms*	*Symptoms in field observation*	*Symptoms in controlled application*	*Month of observation*	*Author*
Abies alba	<0.05	–	0.05-1.0	–	Sury and Flückiger (1983)
Abies fraseri	0.016-0.02	–	–	Sep/Nov	Robarge *et al.* (1989)
Acer negundo	<0.06	0.71-0.86	–	Jan–Apr	Lumis *et al.* (1976)
	–	0.04	–	Aug	Sucoff (1975)
Acer platanoides	0.03	–	1.02	–	Dirr (1978)
	0.005-0.01	0.0163-0.23	–	–	Krapfenbauer (1976)
	0.10	0.11	–	Jun	Kydar (1981)
	–	0.163	–	Jun/Jul/Aug	Leh (1973)
	<0.06	0.19-0.22	–	Jan–Apr	Lumis *et al.* (1976)
Acer pseudoplatanus	–	0.93	–	Jun/Jul/Aug	Leh (1973)
Acer saccharinum	0.001-0.018	0.004-1.48	–	Apr/Jun/Sep	Hanes *et al.* (1970b)
	–	0.04	–	Aug	Sucoff (1975)
Acer saccharum	–	<0.22	0.29	Aug	Button and Peaslee (1970)
	–	0.04-0.263	–	Aug	Hall *et al.* (1973)
	0.03	–	0.06-0.13	Aug	Hanes *et al.* (1970c)
	0.0008-0.084	0.0057-0.0530	–	Jul	Holmes and Baker (1966)
	0.01-0.03	0.01-0.73	–	Aug	Kotheimer (1967)
	<0.06	0.32-0.42	–	Jan–Apr	Lumis *et al.* (1976)
	0.0015-0.0017	–	0.082-0.0452	–	Smith and Treaster (1982)
	–	1.0	–	Aug	Sucoff (1975)
Aesculus hippocastanum	0.015-0.027	0.35-1.42	–	–	Blum (1974)
	0.018-0.034	0.15-1.45	–	Jun/Jul/Aug	Leh (1973)
	0.02	0.04	–	Jun/Jul/Aug	Leh (1973)
	0.018-0.03	0.059	–	Jun/Jul/Aug	Leh (1975)
Betula papyrifera	0.02	–	0.15-0.45	Aug	Hanes *et al.* (1970c)
Celtis occidentalis	–	0.03	–	–	Sucoff (1975)
Elaeagnus angustifolia	0.12-0.3	–	–	Apr	Dirr (1978)
Elaeagnus umbellata	0.16	–	1.03	Apr	Dirr (1978)
Fagus grandifolia	<0.06	0.13-0.40	–	Jan–Apr	Lumis *et al.* (1976)
Fagus sylvatica	0.05	0.42	–	Jun/Jul/Aug	Leh (1973)
Forsythia × *intermedia*	0.1-0.6	–	–	Aug	Hanes *et al.* (1970d)
Gleditsia triacanthos	0.02-0.12	–	–	Aug	Hanes *et al.* (1970c)
Juniperus chinensis	0.04	–	–	Aug	Hanes *et al.* (1970e)
Juniperus horizontalis	0.01	–	0.07-1.0	Aug	Hanes *et al.* (1970e)
Ligustrum amurense	<0.06	0.14	–	Jan–Apr	Lumis *et al.* (1976)
Ligustrum vulgare	<0.07	–	0.04-1.5	Aug	Hanes *et al.* (1970d)
Lonicera tatarica	–	–	0.3-0.8	Aug	Hanes *et al.* (1970d)
Malus sylvestris	–	0.28-0.66	–	May	Hofstra and Lumis (1975)
	<0.06	0.28-0.41	–	Jan–Apr	Lumis *et al.* (1976)
Picea abies	0.20	–	0.10	Aug	Hanes *et al.* (1970e)
	0.01-0.02	0.02-0.06	–	Apr	Hutchinson *et al.* (1967)
Picea rubens	0.01-0.019	–	–	Sep/Nov	Robarge *et al.* (1989)
Pinus mugo	0.06	0.32-0.78	–	May	Hofstra and Hall (1971)
Pinus nigra	0.02-0.08	0.48-0.65	–	May	Hofstra and Hall (1971)
	<0.06	0.21-0.32	–	Jan–Apr	Lumis *et al.* (1976)
Pinus ponderosa	0.02	–	0.34	–	Scharpf and Srago (1974)
	0.01	–	0.01-1.40	–	Spotts *et al.* (1972)
	0.02-0.08	–	0.04-1.4	–	Staley *et al.* (1968)

Table 1.3 continued.

	Leaf Na^+ (% oven dry weight)				
Species	*No symptoms*	*Symptoms in field observation*	*Symptoms in controlled application*	*Month of observation*	*Author*
Pinus radiata	0.6-0.8	1.98	–	Apr	Potts (1978)
Pinus resinosa	0.1	0.02-0.13	–	Apr	Hutchinson *et al.* (1967)
Pinus strobus	<0.05	–	0.03-0.05	Aug	Hanes *et al.* (1970e)
	0.02	0.06-0.16	–	May	Hofstra and Hall (1971)
	<0.06	0.58-0.97	–	Jan–Apr	Lumis *et al.* (1976)
Pinus sylvestris	–	0.26-1.32	–	May	Hofstra and Hall (1971)
	<0.002	0.002-0.004	–	Jun/Jul/Aug	Leh (1973)
Populus sp.	0.09	0.34	–	Jun/Jul/Aug	Leh (1973)
Prunus besseyi	0.30	–	2.20	Apr	Dirr (1978)
Prunus tomentosa	0.50	–	1.45	Apr	Dirr (1978)
Rhus glabra	0.30	–	0.77	Apr	Dirr (1978)
Robinia pseudoacacia	0.006-0.015	–	–	Jun/Jul/Aug	Leh (1973)
Rosa rugosa	0.50-0.52	–	–	Apr	Dirr (1978)
Salix alba	<0.06	1.93-2.00	–	Jan–Apr	Lumis *et al.* (1976)
Salix pentandra	0.05	–	–	–	Edwards *et al.* (1981)
Sorbus aucuparia	0.039	–	0.25-0.47	–	Semoradova and Materna (1982)
Spiraea × *vanhouttei*	–	–	0.2-0.5	Aug	Hanes *et al.* (1970d)
Syringa vulgaris	<0.06	0.18-0.33	–	Jan–Apr	Lumis *et al.* (1976)
Thuja occidentalis	<0.8	–	>0.8	–	Foster and Maun (1978)
	–	0.19-0.35	–	–	Hofstra *et al.* (1979)
	0.04	0.02	–	Apr	Hutchinson *et al.* (1967)
	<0.06	0.40-0.46	–	Jan–Apr	Lumis *et al.* (1976)
Tilia cordata	0.11	0.06	–	Jun	Kydar (1981)
	0.012-0.013	0.107-1.53	–	Jun/Jul/Aug	Leh (1973)
	0.02	0.58	–	Jun/Jul/Aug	Leh (1973)
	0.025-0.033	0.149-0.551	–	Jun/Jul/Aug	Leh (1975)
Tilia × *europaea*	0.025	0.42-0.89	–	Jun/Jul/Aug	Leh (1973)
Tilia tomentosa	0.035	0.48	–	Jun/Jul/Aug	Leh (1973)
Tsuga canadensis	–	0.03-0.13	–	Apr	Hutchinson *et al.* (1967)

Chapter 2

Species Tolerance to De-icing Salt

Introduction

It must be borne in mind at the outset of an attempt to review salt tolerance that no species is immune to damage. Even the most tolerant plants die if they are exposed to salt in sufficiently high concentrations. It must also be remembered that although tolerance is a genetically controlled characteristic, its expression may be modified by a considerable number of environmental factors. As salt tolerance is largely governed by genetic factors it follows that some groups of plants will be more tolerant than others: for example, herbaceous plants are generally considered to be more tolerant than woody plants (Westing, 1969; Davison, 1971; Kydar, 1981), and it has been suggested that broadleaves are more tolerant than conifers (Werkhoven *et al.*, 1966; Hanes *et al.*, 1970a). Although the reasons for these differences are not well understood, it appears that woody plants may be prone to accumulating higher concentrations of sodium and chloride in their tissues, and are at the same time more sensitive to these ions than herbaceous species. Even within a single genus there may be considerable variation in tolerance (Plate 15). Advantage needs to be taken of these genetic differences so that plants with the greatest tolerance to salt can be planted in areas where damage from de-icing salt occurs, or is likely to occur.

This Bulletin reviews the variation in resistance to salt of a wide variety of species. A list of the reported tolerance of some 332 woody species has been compiled from the literature and is the most comprehensive one of its kind yet produced (Table 2.1). The methods used for assessing salt tolerance have also been summarised and the reasons for variation in performance have been discussed. Finally, recommendations for research to identify salt tolerant species and to examine further the mechanisms of salt tolerance are made.

Methods of assessing salt tolerance

Numerous techniques have been used to assess salt tolerance, and these fall broadly into two categories; observations made in the field and assessments made during controlled experiments. Observations in the field are not limited solely to the effects of de-icing salt as plants are injured by salt from many sources. Thus information can accrue from observations made in areas that have been inundated from the sea, or are exposed to salt laden winds from the sea, and can also come from semi-arid regions where salinity of the soil is a major problem because of poor quality irrigation water.

The published information on relative salt tolerance from field observations has sometimes been very subjective, but more often has been based on reasonably objective survey techniques. An example of the latter is given by Lumis *et al.* (1976) who assessed the salt tolerance of 72 species found along major highways in Ontario by scoring damage on a scale of 1–5; a rating of 1 indicating no dieback or needle browning of conifers, and no dieback, tufting, or inhibition of flowering of broadleaved species, and a rating of 5 indicating complete branch dieback and needle browning of conifers, and complete dieback, evidence of previous tufting, and lack of flowering of broadleaved species. Ratings of 2, 3 and 4 encompassed 'slight', 'moderate' and 'extensive' gradations of the above injury symptoms. Trees in category 1 were

Table 2.1 Summary of literature reports on the relative tolerance to salt of 332 woody species. Species are classified as tolerant (T), moderately tolerant (MT), intermediate (M), moderately susceptible (MS) or susceptible (S). Numbers correspond to the references (listed at end of Table) from which the data were obtained. Reports are divided into those derived from field observations and those derived from controlled applications. These two categories are subdivided into tolerance to salt spray and tolerance to soil salt (beside trunk roads damage is primarily as a result of salt spray; in town/city streets, damage is primarily as a result of soil salt).

	Field observation		***Controlled application***		
Species	*Trunk roads*	*Town/city streets*	*Salt spray*	*Soil salt*	*General observation or circumstances unknown*
Abies grandiflora				S_{18}	
A. alba	T_{16} M_{17}				
A. balsamifera				S_{41}	
Acer campestre	T_{8} $M_{15,35}$ MS_{36}		MS_{4}	M_{19} MS_{4}	T_{45} M_{9}
A. ginnala	$M_{8,42}$	M_{42}	S_{7}	M_{24}	$T_{9,45}$
A. negundo	$S_{29,30}$	M_{7}	M_{53}	MS_{45} M_{51}	
A. platanoides	$T_{29,30,42}$ $M_{15,35}$ S_{36}	M_{42} $S_{22,26,27}$	T_{7} MS_{4}	T_{53} $M_{13,19,24,52}$ MS_{4} S_{23}	T_{9} MS_{45} S_{40}
A. pseudoplatanus	$M_{8,35}$	$S_{22,26,27}$	S_{4}	MS_{19} $S_{4,23,38}$	T_{9} $S_{21,28,40}$
A. rubrum	M_{29} $S_{39,42}$	S_{42}			
A. saccharinum	MT_{29} M_{42}	M_{27}	$M_{26,42}$	M_{7}	
A. saccharinum 'Wieri'		S_{27}			
A. saccharum	T_{29} MT_{30} $S_{39,42}$	S_{42}		$M_{6,20,39}$ $S_{22,25}$	M_{5}
A. tataricum	S_{42}			S_{7}	
Aesculus × *carnea*		$S_{22,26,27}$			
A. glabra		$S_{22,27}$			
A. hippocastanum	T_{29}	$S_{22,26,27}$	T_{7} S_{4}	T_{52}, $S_{4,19}$	$S_{3,27,40}$
Ailanthus altissima	T_{29}	T_{27}		S_{6}	
A. glandulosa				M_{38}	
Alnus hirsuta			M_{7}		
A. glutinosa	$M_{8,15,35}$		$T_{4,7}$	T_{4} $M_{19,23}$ S_{53}	M_{9}
A. incana	M_{8} S_{45}	M_{22}	M_{7} S_{4}	$S_{4,19,53}$	T_{9} S_{28}
A. rugosa	M_{29} S_{39}				
A. viridis	M_{8}		S_{4}	S_{4}	M_{9}
Amelanchier alnifolia				T_{44}	
A. × *grandiflora*			S_{7}		
A. laevis	S_{29}				
A. ovalis			T_{7}	S_{19}	
Amorpha fruticosa					$T_{37,43,45}$
Arbutus unedo				MS_{18}	
Atriplex hastata				M_{53}	
A. semibaccata				T_{53}	
A. vesicaria				M_{53}	
Berberis koreana			M_{7}		
B. thunbergii	MT_{29} S_{8}		S_{7}	$S_{32,33}$	S_{9}
B. vulgaris			S_{7}		
Betula alleghaniensis	T_{39}				
B. humilis			S_{7}		
B. kighisorum				T_{53}	
B. lenta	T_{39}				
B. papyrifera	T_{39} $M_{29,42}$	M_{42}			
B. pendula	M_{8}	T_{26}	M_{7}	$M_{20,24}$	$M_{5,9}$
B. populifolia	T_{39} M_{29}				
B. pubescens			S_{7}	S_{19}	
Betula sp.				M_{23}	
Buxus microphylla var. *japonica*				M_{2}	

Table 2.1 continued.

Species	*Field observation*		*Controlled application*		*General observation or circumstances unknown*
	Trunk roads	*Town/city streets*	*Salt spray*	*Soil salt*	
Callistemon viminalis				MT_2	
Caragana arborescens	$T_{29,35,36,42}$ M_8		T_7	T_{44} M_{19}	M_9
Carpinus betulus	M_8 S_{35}	$S_{15,22,26,35}$	S_4	$S_{4,19,23,28}$	M_9 S_{21}
C. caroliniana	S_{39}				
Carya ovata	T_{29} S_{39}				
Catalpa speciosa	M_{29}			S_6	
Cedrus atlantica					T_{45}
Celtis australis		T_{22}			
C. occidentalis	S_{42}	M_{42}	S_7		
Cercis canadensis				M_{20}	
Chamaecyparis lawsoniana					T_{45}
C. pisifera			S_7		
Chamaerops humilis				MT_{18}	
Chaenomeles speciosa	M_{29}				
Clematis vitalba			S_7		
Cornus alba			MS_4, S_7	MS_4	
C. alba 'Kesselringii'			S_7		
C. alba 'Sibirica'			S_7		
C. alba 'Spaethii'			S_7		
C. amomum			S_7		
C. florida				S_7	
C. mas	M_8		$S_{4,7}$	$S_{4,19}$	M_9
C. racemosa	M_{29}				
C. sanguinea	M_8 $S_{15,35,42}$		MS_4 S_7	MS_4	T_{45} M_9
C. stolonifera	$S_{29,30}$				
C. stolonifera 'Flaviramea'	S_{42}				
Corylus americana	$S_{8,15}$		S_7		
C. avellana	S_{35}			S_{19}	$S_{9,28}$
C. colurna		$S_{22,26,27}$			T_{45}
C. cornuta			S_7		
Cotoneaster acutifolius					T_{45}
C. amoenus					T_{45}
C. congestus				S_{18}	
C. dielsianus	S_8				S_9
C. divaricatus	S_8		S_7		
C. foveolatus					T_{45}
C. franchetii					T_{45}
C. integerrimus			S_7		
C. lucidus				M_{24}	
C. moupinensis					T_{45}
C. multiflorus					T_{45}
Crataegus crus-galli	S_{42}	S_{42}	S_7		
C. monogyna	T_{10} M_8 $S_{15,36}$	S_{22}	M_4 S_{35}	$M_{4,19}$	T_{45},M_9
C. oxyacantha	M_8 S_{35}	$S_{22,26,27}$	MT_4	MT_4	M_9
C. punctata			S_7		
Crataegus spp.	MS_{29}				
Cydonia oblonga	M_{29}				
Cytisus scoparius	M_{10}				
Elaeagnus angustifolia	$T_{8,42}$ MT_{29} M_{36}	T_{42}	M_7 S_{35}	$T_{13,31,32,33,51}$ $M_{38,44,53}$	$T_{9,12,37,43,45}$
E. commutatus					$T_{37,43}$
E. × *ebbengei*			S_7		

Table 2.1 continued.

Species	Field observation: Trunk roads	Field observation: Town/city streets	Controlled application: Salt spray	Controlled application: Soil salt	General observation or circumstances unknown
E. pungens				M_{2}	
E. umbellata			S_{7}	S_{13}	
Euodia daniellii					T_{45}
Euonymus alatus	MT_{29}			$S_{32,33}$	
E. europaeus	$T_{20,35}$ M_{8}		M_{4} S_{7}	T_{19} M_{4}	S_{9}
E. japonicus				MT_{2}	
E. verrucosus			S_{7}		
Fagus grandifolia	$S_{29,30}$			M_{41}	
F. sylvatica	M_{35} $S_{15,35}$	$S_{22,26,27}$	MS_{4}	MS_{4} $S_{19,23}$	S_{28}
Forsythia × *intermedia*	M_{29}			M_{20}	
Fraxinus americana	$T_{39,42}$			T_{39}	
F. angustifolia		T_{42}	M_{7}		M_{45}
F. excelsior	M_{15} MS_{36} S_{42}	$M_{22,26,27}$ S_{42}	M_{4}	T_{23},$M_{4,6,19,38}$	$M_{21,26}$
F. pennsylvanica	M_{42}	M_{42}		$T_{33,44}$ M_{32} $S_{20,31}$	M_{45}
Ginkgo biloba				T_{48}	
Gleditsia triacanthos	$T_{26,27,42}$	$T_{22,26,27}$	S_{7}	$T_{20,32,33,46,48}$	MS_{45}
G. triacanthos var. *inermis*		T_{42}			T_{12}
Halimodendron halodendron			T_{7}		
Hedera canariensis				S_{2}	
Hibiscus rosasinensis cv Brilliant				S_{2}	
Hippophae rhamnoides	$T_{8,35}$ MS_{36}		T_{4} M_{7}	$T_{4,19,53}$	$T_{9,12,34}$
Ilex aquifolium	M_{10}				
Juglans nigra	T_{29}	M_{27}		$S_{32,33}$	
J. regia	T_{29}	S_{22}		M_{19}	
Juniperus chinensis				T_{20} M_{2}	
J. horizontalis				T_{20}	
J. virginiana	T_{39} M_{42}			$M_{32,33}$ S_{31}	
Koelreuteria paniculata					S_{45}
Kolkwitzia amabilis	M_{29}				
Larix decidua			T_{7}	S_{38}	
L. leptolepis			T_{7}		
Ligustrum amurense	MT_{30}			T_{20}	T_{5}
L. lucidum				M_{2}	
L. ovalifolium	S_{35}			S_{19}	
Ligustrum spp.	M_{29}				
L. vulgare	$S_{8,15,35,36}$		MT_{4}	MT_{4} M_{19} S_{53}	$T_{21,45}$ S_{9}
Liriodendron tulipifera				M_{25} S_{20}	
Lonicera × *amoena* var. *alba*			S_{7}		
L. coerulea			S_{7}		
L. japonica				$M_{32,33}$ S_{31}	
L. maackii			S_{7}		
L. periclymenum			T_{7}		
L. tatarica	$T_{35,42}$		S_{7}	$T_{19,20}$ S_{44}	$T_{5,45}$
Lonicera spp.	T_{29}				
L. xylosteum	$T_{10,35}$ $M_{15,36}$ S_{8}		$M_{4,7}$	T_{19} M_{4}	S_{9}
Lycium barbarum	T_{35} MS_{36}		T_{7}	$T_{19,53}$	$T_{37,28}$
Mahonia aquifolium				S_{18}	
Malus baccata				S_{44}	
M. 'Dolgo'	S_{42}				

Table 2.1 continued.

Species	***Field observation*** *Trunk roads*	*Town/city streets*	***Controlled application*** *Salt spray*	*Soil salt*	*General observation or circumstances unknown*
M. 'Hopa'	S_{42}				
M. 'Radiant'	S_{42}				
Malus spp.	MT_{29} M_{29}				
M. sylvestris	$M_{30,35}$		T_{7}	M_{19}	
Morus alba	S_{29}		S_{7}		
M. nigra				T_{19}	
Nandira domestica				S_{2}	
Nerium oleander				MT_{2}	
Paulownia tomentosa					T_{45}
Philadelphus spp.	MT_{29}				
Photinia × *fraseri*				S_{18}	
Picea abies	M_{29} $S_{14,16,17}$		$S_{4,7}$	$S_{4,20,23\ 38}$	
P. glauca	S_{29}			$S_{41,53}$	
P. glauca 'Densata'	T_{42}	T_{42}			
P. omorika			S_{4}	S_{4}	
P. pungens	$T_{29,42}$	M_{42}		T_{23} $S_{32,33}$	
Pinus aristata			M_{49} S_{47}		
P. ayacahuite var. *brachyptera*			$M_{47,49}$		
P banksiana (divaricata)	T_{29}		S_{49}		
P. cembra			T_{47} $S_{7,49}$		
P. densiflora			S_{49}		
P. halepensis				MT_{18}	
P. mugo	$T_{17,29}$			$T_{38,52,53}$	
P. nigra	$T_{17,30,42}$ MT_{29}	T_{42}	T_{49}		T_{1}
P. parviflora			$M_{47,49}$		
P. peuce			$S_{47,49}$		
P. ponderosa			T_{49}	T_{33} M_{32}	
P. resinosa	$S_{29,39,42}$	M_{42} S_{42}	M_{49}		
P. strobus	$T_{16,17}$ $S_{29,30,39}$		$S_{47,49}$	$M_{41,46,48}$	$T_{5,45}$ S_{1}
P. sylvestris	M_{42},MS_{17} $S_{16,29}$	M_{42}	M_{49} S_{7}	M_{23}	
P. thunbergii			$T_{47,49}$	M_{18}	T_{12}
P. wallichiana					T_{45}
Pittosporum tobirus				S_{2}	
Platanus × *hispanica*	T_{35}	$M_{22,26,27}$	MS_{4}	M_{19} MS_{4}	T_{40} M_{21}
P. occidentalis				$S_{46,48}$	
Podocarpus macrophyllus				S_{18}	
Populus × *acuminata*				T_{53}	
P. alba	T_{42}	T_{42}	T_{7}	$T_{19,53}$	$T_{21,28,45}$
P. angustifolia				T_{53}	
P. balsamifera		M_{27}		T_{53} S_{53}	
P. × *berolinensis*	M_{26}	M_{22}			
P. × *canadensis*			T_{7}	T_{53} M_{19}	MT_{45} M_{21}
P. canescens			T_{7}	$T_{19,53}$	$T_{21,28}$
P. deltoides	$T_{29,42}$	M_{42}		T_{53} M_{41} S_{53}	
P. grandidentata	T_{39} M_{29}				
P. laurifolia				$S_{51,53}$	
P. nigra	M_{8}		T_{7}	$M_{19,53}$	
P. nigra 'Italica'	M_{29}			S_{53}	S_{28}
P. 'Oxford'			T_{4}	T_{4}	
P. 'Rochester'			MT_{4}	MT_{4}	

Table 2.1 continued.

Species	*Field observation*		*Controlled application*		*General observation or circumstances unknown*
	Trunk roads	*Town/city streets*	*Salt spray*	*Soil salt*	
P. sargentii				T_{53}	M_{21}
P. simonii		$M_{22,26}$			S_{45}
Populus spp.	MT_{29}				
P. tremula	T_{35}	M_{22}		T_{19}	
P. tremuloides	T_{39} M_{29}			T_{53} M_{41}	
P. trichocarpa				T_{53}	
Potentilla fruiticosa	T_{42} S_{8}				S_{9}
Prunus americana				S_{44}	
P. avium	T_{35}	$S_{26,27}$			T_{45}
P. besseyi				M_{13}	
P. cerasifera					T_{45}
P. mahaleb				S_{19}	
P. nigra				M_{41}	
P. padus	M_{35}		M_{7} S_{8}	T_{53} M_{19}	S_{9}
P. serotina	$T_{35,39}$ $S_{8,15}$		S_{7}	T_{6} M_{19} S_{23}	$S_{9,45}$
P. serrulata 'Kanzan'	S_{8}	S_{26}			
P. simonii		M_{27}			
P. spinosa				T_{19}	T_{45} S_{9}
P. tenella					T_{45}
P. tomentosa				S_{13}	T_{45}
P. virginiana	T_{29}			M_{44}	
Pseudotsuga menziesii	$S_{16,17}$		M_{7} S_{7}	$S_{9,23,31,33}$	MT_{45}
Pyracantha graberi				M_{2}	
Pyrus baccata				M_{51}	
P. pyraster	M_{42}				T_{45}
Quercus alba	T_{39}			$T_{41,53}$	
Q. bicolor			S_{7}		
Q. borealis				T_{41}	
Q. cerris					T_{45}
Q. imbricaria					T_{45}
Q. libani					T_{45}
Q. macrocarpa	M_{29}		M_{7}	T_{53}	T_{45}
Q. muhlenbergii			S_{7}		
Q. palustris	S_{42}	S_{42}	S_{7}	M_{46}	
Q. petraea				$T_{19,23}$	M_{6}
Q. robur	T_{26} M_{8}	$T_{22,27}$	M_{4}	$T_{19,23,28,38}$ M_{4}	$T_{21,40,45}$
Q. rubra	$T_{29,39}$ M_{8}	$T_{22,26,27}$	MS_{4} S_{7}	$T_{38,53}$ MS_{4}	T_{40} MS_{9}
Rhamnus cathartica	T_{29} M_{8}		M_{7}		
R. crenatus			M_{7}		
R. frangula	$M_{8,29}$		T_{7}	M_{19}	
Rhaphiolepsis indica				M_{18}	
Rhus glabra	M_{42}	M_{42}		M_{13}	
R. trilobata				$T_{31,32,33}$	
R. typhina	T_{29}				
Ribes alpinum	T_{35} $M_{8,15}$		$T_{7,19}$		M_{9}
R. americanum			M_{7}		
R. aureum	M_{8}		T_{7}	T_{24}	M_{9}
R. divaricatum			M_{7}		
R. magdalenae			S_{7}		
R. nigrum			T_{7}	M_{51}	
Robinia pseudoacacia	$T_{17,29,39}$ M_{8}	$T_{22,26,27}$	T_{7} MT_{4}	$T_{9,19,23,31,33,38,51}$ MT_{4}	$T_{12,21,28,34}$ M_{45}

Table 2.1 continued.

Species	Field observation: Trunk roads	Field observation: Town/city streets	Controlled application: Salt spray	Controlled application: Soil salt	General observation or circumstances unknown
Rosa canina	$S_{15,35}$		S_7		S_9
R. multiflora				$S_{20,32,33}$	S_9
R. pimpinellifolia	T_{10}				
R. rugosa	T_{35} M_{15} MS_{36}		S_7	$T_{13,19}$	T_9
Rubus fruticosus	S_{35}				
Salix alba			T_7	$T_{19,32}$	T_{50} M_{11}
S. alba 'Tristis'	M_{29} S_{30}				
S. alba 'Vitellina'	M_{42}	M_{42}	MT_4 S_7	MT_4 M_{31}	M_{11}
S. × *alepecuroides*					T_{11}
S. × *amygdalina* (*triandra*)			T_7		
S. aurita			S_4	S_4	
S. 'Basfordiana'					S_{11}
S. caprea	$M_{8,15,35}$		MT_4 M_7	MT_4	S_9
S. cinerea			M_4	M_4	
S. cordata					M_{11}
S. daphnoides			T_7 MT_4	MT_4	
S. dasyclados					T_{11}
S. fragilis		T_{22}	T_7	T_{53}	T_{11}
S. hippophaefolia					M_{11}
S. incana (*elaeagnos*)			MT_4	MT_4	
S. × *meyerana*					M_{11}
S. nigra	MT_{29}				
S. pentandra	M_{42}	M_{42}			
S. purpurea var. 'Lambertiana'			$T_{4,7}$	T_4 S_{32}	
S. purpurea 'Nana'				S_{33}	
S. × *rubens*			T_4	T_4	S_{11}
S. smithiana			M_4	M_4	
Salix sp.				M_{23}	
S. 'Stipularis'					T_{11}
S. viminalis			MT_4	T_{53} MT_4	$T_{11,50}$
S. × *viridis*	S_8				
Sambucus canadensis			S_7		
S. nigra	M_{42} $S_{8,35}$	M_{42}	S_7	M_{19}	$T_{37,43}$
S. racemosa	$S_{15,35}$				
Shepherdia argentea		T_{42}		$T_{32,33}$ $M_{31,44}$	
Sophora japonica		$T_{22,26,27}$		$T_{46,49}$	T_{45}
Sorbus aria		$M_{22,26}$			
S. aucuparia	S_8	$M_{22,26,27}$	$S_{4,7}$	$S_{4,19,38}$	
S. decora (*scopulina*)			T_7		
S. intermedia		M_{26}	S_7	M_{19}	
S. latifolia			S_7		
S. nigra		M_{27}			
Sorbus spp.	MT_{29}				
Spiraea × *arguta*	M_8				
S. × *bumalda*	$M_{29,42}$				
S. × *vanhouttei*				$S_{9,20}$	T_{45}
Stephanandra incisa	S_8				
Symphoricarpos albus			M_7		
S. albus var. *laevigatus*	$M_{15,35}$			T_{19}	
S. × *chenaultii*	S_8				T_{45}

Table 2.1 continued.

	Field observation		***Controlled application***		
Species	*Trunk roads*	*Town/city streets*	*Salt spray*	*Soil salt*	*General observation or circumstances unknown*
S. orbiculatus		$S_{8,42}$	S_7		
S. racemosus				T_{53}	
Syringa amurensis	T_{29}				
S. vulgaris	T_{29} M_{42} $S_{8,30}$		S_7	M_{44} S_{44}	T_{45} M_{21}
Taxus baccata	M_{10}				
Taxus spp.	MS_{29}				
Tamarix gallica	T_{10}			T_9	
T. odessana					$T_{37,43,45}$
T. pentandra			T_7	$T_{33,53}$	$T_{37,43}$
T. tetrandra					$T_{37,43,45}$
Thuja occidentalis	$M_{29,30,42}$	M_{42}			
T. orientalis				M_2	T_{45}
T. plicata					T_{45}
Tilia americana	M_{42} $S_{39,42}$				
T. cordata		M_{42} $S_{8,22,26}$	T_7 S_4	T_{52} $M_{19,53}$ $S_{9,23,24,33,47}$	
T. × euchlora					S_{40}
T. × europaea					M_{40}
T. occidentalis		S_{42}			
T. platyphyllos		$S_{22,26}$	T_7 MS_4	MS_4 $S_{23,24}$	
T. tomentosa					T_{34}
Tremula vulgaris				M_{38}	
Tsuga canadensis	$S_{29,39}$			M_{41} S_{20}	
Ulex europaeus	T_8 M_{10}				M_{40}
Ulmus americana	MT_{29} M_{42} S_{39}	M_{42}		$T_{41,53}$	
U. campestris (procera)		S_{22}	MS_4	MS_4	T_{28}
U. carpinifolia	M_{35}	$S_{26,27}$			T_{45} M_3
U. glabra	T_{35} M_{15}	$S_{22,26,27}$	T_7	$T_{19,23}$ M_{53}	T_{21}
U. × hollandica				M_{19}	M_{45}
U. laevis				M_{23}	MT_{45}
U. pumila	MT_{29}			T_{53}	
U. pumila var. *arborea*		$T_{26,27}$	S_7		T_{45}
Virburnum lantana	T_8 $S_{36,42}$		S_7		
V. opulus	MT_{29} M_{35} S_{10}		S_7	M_{19}	
V. tinus var. *robustum*				S_2	
Weigela 'Eva Rathke'				M_{20}	
Yucca filamentosa				T_{20}	

Authors:

1. Barrick *et al.*, 1979
2. Bernstein *et al.*, 1972
3. Blum, 1974
4. Braun *et al.*, 1978
5. Brod and Preusse, 1975
6. Brogowski *et al.*, 1977
7. Buschbom, 1968
8. Chrometzka and Dittenberg, 1974
9. Chrometzka, 1974
10. Colwill *et al.*, 1982
11. Dimitri, 1973
12. Dirr, 1976
13. Dirr, 1978
14. Dragsted, 1973
15. Emschermann, 1973
16. Evers, 1974
17. Evers, 1976
18. Francois and Clark, 1978
19. Glasau, 1966
20. Hanes *et al.*, 1976
21. Hvass, 1970
22. Krapfenbauer, 1976
23. Kreutzer, 1977
24. Kydar, 1981
25. Lacasse and Rich, 1964
26. Leh, 1973
27. Leh, 1975
28. Linde and Meiden, 1954
29. Lumis *et al.*, 1973
30. Lumis *et al.*, 1976
31. Monk, 1960
32. Monk and Wiebe, 1961
33. Monk and Petersen, 1962
34. Ruge, 1971
35. Sauer, 1967
36. Schiechtl, 1978
37. Schmidt, 1977
38. Semoradova and Materna, 1982
39. Shortle and Rich, 1971
40. Stach, 1969
41. Strong, 1944
42. Sucoff, 1975

43. Timm *et al.*, 1976
44. Tinus, 1984
45. Toth, 1972
46. Townsend, 1980
47. Townsend, 1983
48. Townsend, 1984
49. Townsend and Kwolek 1987
50. Wentzel, 1973
51. Zhemchuznikov, 1946
52. Zulauf, 1965
53. Zulauf, 1966

considered tolerant and trees in category 5 were considered sensitive to injury from de-icing salt and prone to die with repeated applications. Similar methods have been used for determining the salt tolerance of trees and shrubs alongside roads in Minnesota (Sucoff, 1975), southeastern New Hampshire (Shortle and Rich, 1971), and Michigan (Davidson, 1970), and alongside autobahns (e.g. Sauer, 1967; Chrometzka and Dittenberg, 1974; Schiechtl, 1978) and town and city streets (e.g. Leh, 1973; 1975; Petersen and Eckstein, 1988) in Germany.

Experiments can be divided into two main categories; those which assess the tolerance of plants to salt in their root environment, and those which assess tolerance to salt spray. The specific symptoms of salt damage, and their severity, can vary significantly depending on whether salt spray or salt contaminated soil is the main cause of injury (see Chapter 1). Within these two categories a variety of methods have been employed. It must be recognised, however, that there are the 'controlled' procedural parts of the experiment such as frequency of salt application and application rate, and the 'uncontrolled' components of experiments which most often are due to the vagaries of the weather, which may also have a significant influence on the experimental results. The procedures which have been used for assessing salt tolerance are outlined below and the environmental factors influencing salt tolerance are considered later.

As would be expected when assessing tolerance to salt in the soil most authors have used either potted plants, or juvenile trees grown in field plots, or both. During one or more dormant seasons salt has then either been added to the soil as a solid or as a solution. There has usually been an attempt to apply doses which relate to those used in current practice. (Average annual rates of application to roads are in the order of 1000–5000 g m^{-2}; Thompson and Rutter, 1986.) Assessment of injury has usually taken place at some stage after new growth has started using visual symptoms and measurements of growth to score health. The specific ways in which experiments have been carried out have varied considerably, however, often making comparisons of the results from one author with another difficult.

Semoradova and Materna (1982), in Czechoslovakia, planted trees in pots during spring and added salt solution to the soil eight times during the following two dormant periods. Assessments were then made of mortality, height and weight increments, and Cl^- content of the leaves. Braun *et al.* (1978), in Germany, also used potted trees and exposed 43 species to salt in the soil, salt spray, or a combination of both. In the soil salting experiment NaCl was added, in solution, to potted trees 10 times per year during three dormant periods. Measurements were made of visible foliar damage, shoot length and Cl^- content of twigs after each salting season. Complementing the above trial a further experiment conducted at the same time used 20–25-year-old trees of four species growing in a tree nursery which were treated with salt applied directly to the ground, with varying annual doses over the three years. The results from the pot experiment and the field trial were compared.

Kydar (1981) in the Soviet Union used 1-year-old seedlings of six species planted during July 1976 in peat enriched soil, and added NaCl and KCl, dissolved in water, to the soil in August of that year. In the following year salt was added to the soil again on three occasions in May, June and August. This experiment highlights one of the problems with some of the experimental techniques used in the past in that the conditions did not reflect those occurring after road-salting. Plants were exposed to elevated salt concentrations very soon after planting, and at a time of the year (summer) when concentrations in the soil are normally approaching their lowest. Results from experiments carried out during active growth may not reflect those obtained from plants exposed to salt during dormancy.

Dirr (1978) used potted 2-year-old seedlings of seven woody species planted in an equal mix of soil:peat:perlite and added NaCl solution to the pots daily for a period of 12 days, also apparently after budbreak. Evaluations were of visible damage and Na^+ and Cl^- content of leaves. Tolerance ratings contrasted somewhat with those reported elsewhere and this was also probably because salt was added to the soil during active growth rather than during dormancy.

Bernstein *et al.* (1972) determined the salt tolerance of 25 species using field plots salinized with NaCl + $CaCl_2$. Salt was added to the plots shortly after planting or after a delay of a few weeks. The delay in salting, not surprisingly, increased tolerance somewhat, but did not alter the tolerance of individual species relative to each other.

Townsend (1980) investigated the salt tolerance of several species in a more artificial way by exposing them to NaCl in a hydroponics system. The 2-year-old seedlings were initially grown in nutrient solution but after leafing out had different concentrations of salt added to the solution. Measurements were made of height growth, fresh and dry weights of roots, stems and leaves, and percentage of foliage showing injury. In order to test whether this technique gave results similar to more traditional methods Townsend (1984) grew the same species in soil or a peat:perlite:sand mix. He found that although there was some variation in the severity of symptoms between the hydroponically grown plants and the plants grown in the two soil types, relative tolerance of the species tested did not change significantly.

Similarly, Bicknell and Smith (1975) assessed salt tolerance indirectly by determining how salt affected the germination and initial growth of several tree species. Seeds were planted in salt amended soil and allowed to germinate. Percentage and timing of emergence were used as the response criteria. Although in their discussion Bicknell and Smith concluded that the influence of salt on seed germination was not closely related to post germination salt tolerance, the percentage germination of the species they tested was in fact broadly in line with the salt tolerance of these species as reported in Table 2.1. Werkhoven *et al.* (1966) also assessed germination, survival, plant height and dry matter yield for four species grown on a saline substrate and found that their results for tolerance supported observations made in the nursery and agreed with observations of others. Tinus (1984) also found reasonable agreement between germination and seedling tolerance for several species. These results therefore suggest that assessing relative salt tolerance from data on germination is a technique which deserves further investigation.

Another technique for evaluating salt tolerance is that of determining protoplasmic salt hardiness. Monk and Wiebe (1961) used stem sections from 3-week-old plants, grown in solution culture, for determining tolerance. These were immersed in salt solution for 24 hours and were then washed and incubated in triphenol tetrazolium chloride (TTC) for a further 24 h. Tolerance was assessed on the basis of tissue survival. Barrick *et al.* (1979) also used the tetrazolium method to investigate the relative tolerance of *Pinus nigra* and *P. strobus*. Both of these studies were conducted on non-salted plants and therefore gave information on intrinsic, or genetic, protoplasmic salt hardiness. Survival of the same species grown in salinized field plots correlated well with the results from the tissue test. However, the tissue tests were limited to 48 h whilst the field tests required from 2 months to 2 years. This technique could therefore be useful for screening a wide range of species for intrinsic salt tolerance due to its rapidity and apparent close correlation with salt sensitivity.

Some authors (e.g. Demeritt, 1973) have naïvely suggested that it is unnecessary to evaluate deciduous species for tolerance to salt spray because they lose their leaves in winter. However, salt may enter twigs of deciduous trees through immature bark, leaf scars and buds and can cause considerable damage and dieback. Indeed, according to Simini and Leone (1986b) the conditions of light, temperature and relative humidity during winter are more conducive to salt uptake from salt spray by certain tree species than conditions in summer. It is therefore important for deciduous species to be screened for susceptibility to de-icing salt spray damage during dormancy.

There are fewer reports detailing experiments which assess the tolerance of plants to salt spray than those which assess tolerance to salt in the soil. However, for the experiments that have been carried out the commonest technique has been to spray the foliage (in the case of conifers, e.g. Barrick *et al.*, 1979; Townsend, 1983; Townsend and Kwolek, 1987) or leafless branches (in the case of deciduous species, e.g. Braun *et al.*, 1978; Simini and Leone, 1986b) of intact trees or seedlings repeatedly with a concentrated salt solution and then observe the ensuing injury. Barrick and Davidson (1980) used 10 cm sections of 1-year-old wood cut from dormant Norway maple trees, which were then placed in moist sand, and sprayed with NaCl for 5 days. Twigs were recut and placed in a greenhouse mist bench in conditions encouraging budbreak. Terminal buds were rated viable if bud break occurred without visible signs of browning and stem tissue was considered viable if no browning of vascular tissue occurred. Buschbom (1968) tested tolerance by dipping shoots, which were still attached to trees, repeatedly in a concentrated salt solution, as did Dimitri (1973), who tested various willow and poplar clones both in the laboratory and in the field. Assessments were made of percentage bud failure and the proportion of tissue showing necrosis or discoloration.

Mechanisms of salt tolerance

It is generally recognised that there are two mechanisms of salt tolerance in plants, *avoidance* and *physiological tolerance* (Buschbom, 1968; Levitt, 1972; Stavarek and Rains, 1983). *Avoidance* has to do with the ability of a plant to exclude high concentrations of salt, and this may occur at a whole plant or cellular level. At the whole plant level low internal concentrations of toxic ions may be maintained despite high levels being present in the external medium, by plants having a low permeability to salts in the roots, stems or needles, or by the roots actively extruding salts back into the external environment. Some halophytic plants are also able to extrude salts that have reached the shoots by excreting them from specialised glands located on the surface of leaves (Marcum and Murdoch, 1990). Exclusion at the cellular level may involve either not allowing ions into the cells in the first place or actively pumping them out once they are in. The former mechanism is obviously preferable (it is thought to involve the preferential absorption of K^+ rather than Na^+) as pumping ions out of cells would involve greater expenditure of energy.

Plants with high concentrations of Na^+ and Cl^- in their tissues tend to be injured while plants with low levels tend not to be injured (Sucoff, 1975). Thus any morphological attribute which enables a plant to exclude salt from its tissues will, not surprisingly, also improve its tolerance. Westing (1969) suggested that oak species are adapted for the avoidance of salt damage because of their deep rooting habit which enables them to avoid areas of the soil where the highest salt concentrations occur (generally the top 10 cm). However, work with juvenile trees has also shown the high salt resistance of this genus indicating that oaks probably possess some mechanism, other than root distribution, which allows them to exclude salt from the roots (e.g. Krapfenbauer, 1976; Kreutzer, 1977). In their survey of roadside trees in Ontario, Lumis *et al.* (1973) found that deciduous plants with resinous buds, e.g. *Aesculus hippocastanum* and *Populus deltoides*, or with buds submerged in the bark, e.g. *Robinia pseudoacacia* and *Gleditsia triacanthos*, were tolerant to salt spray. In the genus *Rhamnus* the species with naked buds (e.g. *R. frangula*) were injured to a greater extent by spray than *R. cathartica* which has scaly buds. They also noted that increased amounts of wax or bloom on spruce needles seemed to add protection. For example, the bluer the spruce (i.e. the waxier the needles) the more resistant it was to spray.

Work on pine species has confirmed that epicuticular wax is amongst the factors contributing to salt tolerance in conifers. Lumis *et al.* (1976) in their survey of roadside trees in Ontario found that *P. nigra* had no twig dieback or needle browning and had a Na^+ content of approximately 0.26% and a Cl^- content of approximately 0.65% and that *P. strobus* had a needle Na^+ content of 0.77% and Cl^- content of 1.12%, and had severe growth reduction and needle browning. Barrick *et al.* (1979) investigated the causes of this difference in susceptibility and found that the salt tolerant *P. nigra* had more wax per unit surface area than the sensitive *P. strobus*. Logan (1975) also found that the tolerant Japanese black pine (*Pinus thunbergii*) had a greater amount of epicuticular wax than the less tolerant eastern white pine (*Pinus strobus*).

Simini and Leone (1986c) in a controlled experiment found that *P. thunbergii* had higher alkane wax content and lower Cl^- concentration than *P. strobus* which had high Cl^- content and low alkane wax. It appears from this study that it is the lengths of the alkane chains that are of greater importance than the total amount of wax in determining salt tolerance, longer chains giving greater resistance to penetration by polar substances than short chains. Anatomical investigations carried out by Dirr (1976) showed that *Pinus thunbergii* needles also have a cuticle-epidermal-subepidermal or hydrodermal layer heavily impregnated with thickenings, which is twice as thick as that of *P. strobus*, and this corresponded to improved resistance to Na^+ and Cl^- penetration of *P. thunbergii* needles. Townsend and Kwolek (1987) also considered that the thickness of the needles might help to exclude salt ions, and found that the cuticle of *P. nigra* was twice as thick as that of *P. strobus*.

Accumulation of Cl^- within needles depends not only on the susceptibility of species to penetration of the toxic ions but also on the propensity of needles to retain salt externally. Some species appear to be able to maintain low external concentrations of Cl^- while others have high external concentrations, at the same application rate (Townsend, 1983). Townsend and Kwolek (1987) assessed the relative tolerance of 13 pine species to salt spray over the course of 3 years. In this evaluation *Pinus ponderosa*, which was the most salt tolerant, had the lowest needle surface Cl^-, internal Cl^-, and internal Na^+, and *P. strobus* had the greatest injury and the highest internal and external levels of Cl^- and Na^+. The retention of salts on the surface of needles probably depends upon topography of the needle surface and the chemical composition of the epicuticular waxes.

Tolerance by avoidance depends not only on the ability to prevent entry of salt into plants but also on their ability to prevent salt penetrating the cells once inside the plant. Foster and Sands (1977) found that there were three areas where salt was stored in the tissues of the moderately susceptible *Pinus radiata*. In the roots, large amounts of Cl^- were precipitated in the hyphae of the mycorrhizae as well as between the cell wall and plasma membrane of the outer cortical cells, suggesting that Cl^- was prevented, in part, from penetrating far into the roots at these sites. In the stem, Cl^- was precipitated in the ray cells (live) and the tracheids (dead) and since tracheids constitute a very large part of pine trees, this site could constitute a considerable sink into which excess salt could be deposited, thus removing it from cellular metabolism. In the needles, the Cl^- was precipitated mainly in the epidermal and sub-epidermal cells and in the mesophyll, being mainly located in the cell walls. Once inside the cells, the majority of evidence suggests that toxic ions are removed to the vacuoles where they are less damaging. However, when the capacity of these 'storage' areas is exceeded or if salinization occurs so rapidly that ions cannot be sequestered quickly enough in areas within the plant where they are not harmful, concentrations in the cytoplasm reach critical levels and plasmolysis and death occur. For example, Sands and Clarke (1977) found that if *P. radiata* was suddenly exposed to salt, rapid uptake of ions occurred leading to subsequent death, but if the salt was applied slowly absorption and sequestration of harmful ions appeared to be better controlled and plants were able to escape visible injury.

Physiological tolerance is the ability of plants to cope with high concentrations of salt within their tissues. Tolerance of this nature involves the ability of plants to maintain favourable water relations, tolerate high cellular levels of ions, and the ability to obtain required nutrients despite the predominance of other ions in the soil. Damage from osmotic imbalance arises when the ability of a plant to absorb water is decreased because of the increased osmotic potential of salty soil, resulting in a 'physiological drought'. Some plants are able to overcome this effect by absorbing salt which redresses the osmotic imbalance allowing water once again to enter the roots. However, the cost of maintaining water uptake is often a reduction in plant growth (Bernstein *et al.*, 1972).

It has already been noted that *Pinus nigra* is more tolerant of salt spray than *P. strobus* and that part of this is because of differences in epicuticular wax amount and chemistry. However, Barrick *et al.* (1979) found that part of this difference was also attributable to the greater physiological tolerance of *P. nigra*. In their experiment, using the tetrazolium test, they found that although a greater amount of Cl^- was found in the tissue of *P. nigra*, the cells of this species had a better survival rate than those of *P. strobus*. In a pot experiment exposing seedlings to salt in the soil, Townsend (1980) found that *Sophora japonica* was considerably more salt tolerant than *Pinus strobus* even though it had a leaf Cl^- content of up to 3% of the dry weight and the Cl^- content of *Pinus strobus* did not exceed 1%. This suggests that *P. strobus* may have been able to exclude Cl^- from its tissues to some extent but that it was more sensitive to the ions that actually entered the plant than *S. japonica*. Other examples of trees which are able to exclude Na^+ and Cl^- to some extent but have a low physiological salt tolerance include *Ulmus campestris*, *Populus* 'Androscoggin' (Braun *et al.*, 1978), *Fagus sylvatica* (Lumis *et al.*, 1976), and *Pinus cembra* (Townsend and Kwolek, 1987).

Sodium chloride in the soil may cause injury because certain ions (e.g. Na^+) are present in much higher concentrations than chemically similar ions (e.g. K^+) and are therefore taken up more readily by the plant. Thus, as Na^+ and Cl^- concentrations in the plant increase, levels of Ca^{2+}, Mg^{2+}, K^+ and P decrease (Stavarek and Rains, 1983). This causes a nutrient imbalance and can often result in the expression of deficiency symptoms (e.g. leaf yellowing). Salt tolerance therefore also depends to some extent on the ability of plants in a saline environment to take up necessary nutrients. However, little is known about this mechanism of salt tolerance for trees.

Influence of extrinsic factors on tree performance

As indicated earlier the intrinsic, or genetically controlled, tolerance to salt of particular species may be modified by many factors, from the tree's age and general vigour to the time of salt application and the prevailing weather conditions. Some of these factors are fairly obvious. Thus it comes as no surprise to find reports that trees in active growth are more susceptible than dormant trees (Buschbom, 1980), and that young trees are generally more sensitive than mature trees (Davidson, 1970; OECD, 1989). The weather may also affect the sensitivity of trees to de-icing salt: for example, frost increases the risk of injury (Bernstein *et al.*, 1972; Sucoff and Hong, 1976), and drought during spring may exacerbate damage (Wester and Cohen, 1968; Burg, 1989). Weather during the preceding growing season may also be important since it partly determines the maturity of the young shoots and therefore their ability to withstand the effects of salt (OECD, 1989). Transplantation shock may be a factor in resistance of young plants, those plants able to establish quickly may be more tolerant than those still suffering from planting shock. Resistance during the initial period of establishment may therefore not be representative of the general tolerance of the species.

Tolerance ranking

Tables ranking species for salt tolerance have been developed by numerous authors. However, these tables are often unreliable and misleading since they are frequently based on limited data and lack a systematic experimental basis. For example, *Acer platanoides* has been classed as tolerant to salt by Zulauf (1966), Buschbom (1968), Lumis *et al.* (1973) and Sucoff (1975) but has also been classed as sensitive by Krapfenbauer (1976), Schiechtl (1978) and Kreutzer (1977) (see Table 2.1). This type of paradox makes it very difficult to make an accurate judgement of the actual salt tolerance of some species. Inconsistencies may arise because of differences in the ways salt tolerance has been assessed, for example, some authors have used growth alone as a measure of tolerance while others have used appearance. Some species experiencing salt stress may maintain rapid growth and have a poor appearance while others may have slow growth but have a good appearance (Bernstein *et al.*, 1972). Differences in experimental procedure, as outlined above, may also affect whether a species is ranked as tolerant or intolerant. One major source of confusion is that some species are tolerant to salt spray but not to soil salt and vice versa. This is illustrated by the fact that *Thuja occidentalis* is reported to be tolerant of relatively high concentrations of salt in the soil but sensitive to low concentrations of foliar applied salts, whereas *Juglans nigra* is reported to be sensitive to salt in the soil but reasonably tolerant of salt spray (Table 2.1). Discrepancies occur repeatedly in the range of medium susceptibility because the demarcation between moderate sensitivity and moderate tolerance is not clear. Thus if a species of intermediate tolerance is compared to a more sensitive species it may appear to be tolerant whereas if it is compared to a more tolerant species it may appear to be sensitive.

The readily available data on the relative tolerance of 332 woody species has been summarised in Table 2.1. In producing this table an attempt has been made to take into account some of the problems outlined above. An indication is therefore given of whether the ranking has been derived from field observations or controlled applications, soil salt or salt spray. The field observations generally relate to mature trees while the experimental observations generally relate to juvenile trees. The distinction between salt contaminated soil and salt spray is obvious for the controlled experiments but is less so for the field observations. Nevertheless, observations made in city streets are almost exclusively of tolerance to soil contamination, and observations made for highways (i.e. rural and trunk roads) are usually of tolerance to salt spray. Making these distinctions enables salt tolerance to be more accurately assessed. However, even if these factors are taken into account there is no clear picture of salt tolerance for the vast majority of the species listed. The table should therefore be used with caution and the reported rankings of particular species should only be accepted when there are a reasonable number of reports (at least 3–4) and when these reports are in agreement with each other. Out of the 332 species in Table 2.1 there are only about 25 species which fulfil these criteria and these are listed below.

The tolerant species are *Caragana arborescens*, *Elaeagnus angustifolia*, *Gleditsia triacanthos*, *Hippophae rhamnoides*, *Pinus mugo*, *P. nigra*, *Populus alba*, *P. canescens*, *Quercus robur*, *Robinia pseudoacacia*, *Salix fragilis*, *S. viminalis*, *Sophora japonica* and *Tamarix* spp.

Species with intermediate tolerance are *Acer saccharum*, *Fraxinus excelsior*, *Pinus sylvestris* and *Salix alba* 'Vitellina'.

Sensitive species are *Acer pseudoplatanus*, *Carpinus betulus*, *Fagus sylvatica*, *Picea abies*, *Pseudotsuga menziesii*, *Rosa canina* and *R. multiflora*.

In an attempt to resolve some of the problems associated with classifying species in order of relative tolerance Table 2.2 was produced. This contains an assessment of the tolerance of a limited number of species relative to three 'marker' species, which from Table 2.1 appear to be consistently tolerant (*Robinia pseudoacacia*), moderately tolerant (*Fraxinus excelsior*), or intolerant (*Acer pseudoplatanus*). Using only those references in the literature which contain all three marker species, and are concerned with tolerance to salt in the soil, the other species were categorised as either more or less tolerant than the marker species. This method appears to give a consistent relative order of tolerance with *Ulmus glabra* being the most salt tolerant and *Acer pseudoplatanus* being the least tolerant. Producing lists of salt tolerance by comparison with species of known tolerance may give a more accurate reflection of the relative salt tolerance of particular species and may, for example, prevent species being classed as tolerant when in fact they are only more tolerant than a selection of sensitive species.

Table 2.2 Tolerance to soil salt of a range of tree species relative to a tolerant (*Robinia pseudoacacia*), intermediate (*Fraxinus excelsior*) and an intolerant (*Acer pseudoplatanus*) species. The first named species is thus the most salt tolerant and the last named species is the least tolerant. Differences in ranking of one or two places are probably not significant.

Tolerance	***Species***
	Ulmus glabra
Tolerant	*Robinia pseudoacacia*
	Quercus robur
	Salix alba
	Gleditsia triacanthos
	Alnus glutinosa
	Elaeagnus angustifolia
	Picea pungens
Intermediate	*Fraxinus excelsior*
	Crataegus monogyna
	Acer campestris
	Picea abies
	Pseudotsuga menziesii
	Aesculus hippocastanum
	Alnus incana
	Sorbus aucuparia
	Fagus sylvatica
	Carpinus betulus
Sensitive	*Acer pseudoplatanus*

Recommended research

There are still many gaps in our understanding of salt tolerance which need to be filled. The mechanisms of salt tolerance are not well understood for the vast majority of tree species. For pines it appears that epicuticular wax and cuticle thickness play an important part in resistance of needles to salt spray, but investigations of this phenomenon have been restricted to a very few species. Mechanisms of exclusion of toxic ions by twigs and roots of woody species have received little attention. The cause or causes of ion exclusion need to be determined for both broadleaved and coniferous species and perhaps thereby it may be possible also to find physiological, biochemical or morphological markers for resistance (Dirr, 1974). Mechanisms of physiological tolerance have similarly been investigated for only a handful of species and are therefore also not well understood.

There is a considerable amount of published information on the responses of a wide range of woody species to salt application (Table 2.1). However, for the vast majority of species there are insufficient data to give a clear and consistent assessment of tolerance. Therefore from this literature review only 25 species out of a total of 332 have been classified according to their salt tolerance with any degree of confidence. This strongly suggests that additional work is necessary if further species suitable for planting in areas where salt is a problem are to be identified. Future work must be carried out in a systematic way bearing in mind the factors which affect salt tolerance, outlined above. Thus, future experiments must investigate tolerance to salt spray in addition to soil salt. Experiments should be designed which use marker species of known tolerance so that the problems associated with ranking species in order can be avoided. Standard procedures for assessing salt tolerance should be adopted so that comparison of one report with another is made easier. To complement standard techniques for assessing tolerance, such as adding salt to the soil around trees and spraying foliage, rapid procedures for screening species for salt tolerance should be developed. From the literature review the tetrazolium and germination tests seem to provide rapid and reasonably reliable techniques which merit further investigation.

Possibilities for increasing the existing salt tolerance of particular species should also be assessed. These may include selection of tolerant genotypes within a species, or improving performance by cultural methods such as fertilisation or addition of gypsum or organic matter to the soil (considered in detail in Chapter 4).

Conclusions

There is a considerable amount of data relating to the tolerance of woody species to salt (Table 2.1) but much of it is either unreliable or inconsistent. Well planned and co-ordinated research needs to be carried out if these problems are to be resolved. Little is known about mechanisms of salt tolerance and research in this area would be valuable as it may identify biological or biochemical markers which could assist in the evaluation of species for resistance to salt damage.

Chapter 3

Mechanisms of Salt Toxicity

Introduction

In order to cause injury salt must first come into contact with plants. De-icing salt reaches the surface of plants as a result of runoff from salt stockpiles, both permanent (Plates 12 and 13) and temporary (Plate 11), and from de-icing operations (Plate 9). In the latter case salt may reach the roadside in a number of ways.

- Through poor salting practices in which a proportion of the salt that is spread lands directly on roadside verges or pavements.
- Through dry salt being thrown to the edge of the road by the action of passing traffic, or by wind.
- Through dissolved salt running off the roads or being splashed or sprayed on to roadside soil and vegetation by passing traffic.
- Through salted snow being blown on to the roadside by snowblowers or being ploughed off by snowploughs.

In the case of motorways, over 90% of the applied salt ends up on the sides of the carriageway along a strip approximately 15 m wide (although salt spray may be carried up to 400 m from the carriageway). The amount deposited decreases exponentially with distance from the roadside (Fromm, 1982; OECD, 1989). In towns where traffic movement is slower the strip may be narrower in width, *c.* 5 m (Ruge and Stach, 1968).

One question that has not yet been resolved is how salt reaches the roots of trees that are growing in paved areas. It is known that trees in this type of situation are damaged by salt (Plate 9) but it is not clear whether injury is solely due to salt accumulating in the small area of soil immediately surrounding the trunk, whether it is caused by salt solution seeping through the gaps between paving slabs, or whether it is due to salt penetrating through supposedly impermeable tarmac. It has been suggested that injury may sometimes be caused by tree roots penetrating drains which carry highly saline runoff from roads, but there is no firm evidence to support this suggestion. If prevention of damage is to be effected for trees growing in paved areas investigations of the route by which salt reaches the roots of trees in this type of site must be undertaken.

Even though salt may come into contact with the external surface of a plant, injury does not arise until the salt reaches the living parts. This may seem an obvious statement but it is not always clear exactly how salt reaches these parts, particularly as with trees and shrubs a large proportion of the plant surface is protected by bark which presents a considerable barrier to salt penetration. Fine roots appear to take up salt readily from contaminated soil. Damage may then occur in this tissue or the salt may be transported through the xylem to other plant parts where injury may also occur. Sodium appears to accumulate in the woody tissue of shoots, but the more mobile Cl^- ions accumulate at the end of the transpiration stream, in the margins and tips of leaves. In plants affected by salt spray, it appears that salt only enters through non-lignified tissue such as buds, leaves and young shoots, and also through leaf and bud scars. However, the exact sites of salt penetration and the relative importance of these sites for injury are unclear.

Physiological mechanisms of salt damage

It has long been established that sodium chloride in high concentrations is damaging to plants. The mechanisms of salt tolerance and salt toxicity have been studied on salt marshes, near sea coasts, and especially in relation to growth of crops on saline soils in semi-arid regions. The interest in this latter topic is not surprising considering the land area affected by salinity. Excluding major saline deserts high soil salt concentrations occur in approximately 400 million hectares, much of it under agricultural production (Stavarek and Rains, 1983; Bongi and Loreto, 1989). With the use of saline water for irrigation this figure increases by several tens of thousands of hectares each year. In the US alone there are 2.2 million hectares of saline soil, and in California, one of the most agriculturally productive states, one-fifth of the irrigated land (approximately 360 000 ha) is affected to some extent by salt (Stavarek and Rains, 1983).

The information which has accrued over many decades of research on saline soils is of great benefit in understanding mechanisms of de-icing salt injury to roadside trees and shrubs. However, the majority of research on salt affected soils has concerned non-woody crop plants which may respond to salt in a different way to woody species. For example, chlorosis is generally not a characteristic symptom of salt injury to herbaceous species (Bernstein, 1975) whereas salt frequently induces chlorosis in trees (Ruge and Stach, 1968; Sucoff, 1975). Similarly, non-woody plants rarely develop leaf burn (Bernstein, 1975) but woody plants frequently exhibit tip and marginal scorch. A degree of caution must therefore be exercised in extrapolating data from herbaceous species to woody species. For this reason most of the information presented here is derived from observations and experiments on woody species although where specific data are lacking reference will be made to research conducted on non-woody species.

The mechanisms of salt toxicity are far from being resolved but two primary processes are thought to be involved. Injury may be caused by salt-induced water stress, sometimes referred to as 'physiological drought' but more properly termed *osmotic stress* (Westing, 1969; Bernstein, 1975), or by ion excess (*specific ion toxicity*) where damage is the result of the specific action of individual ions (Bernstein and Hayward, 1958). It is often impossible to assess with any confidence the relative importance of these effects since they probably interact (Greenway and Munns, 1980). Levitt (1972) suggests that the relative importance of each mechanism differs from species to species and with different environmental conditions. Taken together, however, the combined effects of osmotic and specific ion toxicity include reduced turgor, inhibition of membrane function, inhibition of enzyme activity and photosynthesis, induction of ion deficiency, and an increase in the use of metabolic energy for non-growth processes involved in maintenance of tolerance (Hasagewa *et al.*, 1986).

Osmotic effects

Much of the water movement into and through plants is by osmosis with water moving along a concentration gradient from areas of low to areas of high solute concentration. In uncontaminated soil, water moves rapidly from the dilute soil solution, across a selectively permeable membrane, into the more concentrated cytoplasm of root cells. However, in salt affected soils the soil solution is more concentrated (has a lower *osmotic* or *solute potential*), and this results in a reduced concentration gradient between soil and cell, thus impairing the ability of plants to take up water. This *osmotic* stress is similar to water stress and produces almost identical physiological responses such as increased proline synthesis and decreased stomatal conductance. Stomatal closure reduces water deficit by minimising transpirational water loss, and decreases the movement of Cl^- through the plant and its accumulation at sites of evaporation.

In the main, however, it appears that injury from osmotic stress rarely occurs because plants compensate for the decreased osmotic potential of the soil through a proportional decrease in cellular osmotic potential (Levitt, 1972; Bernstein, 1975), which acts to maintain a relatively constant osmotic gradient between the soil solution and cell cytoplasm. Plants achieve this adjustment either by increasing uptake of inorganic solutes or by increased synthesis and accumulation of organic solutes. Plants which take up inorganic solutes prevent disruption of cellular metabolism by secreting the damaging ions, particularly Cl^-, in the vacuole. The osmotic balance of the cell is maintained by a corresponding increase in the concentration of organic solutes in the cytoplasm. These so-called *compatible solutes* (e.g. sugars, free amino acids and proline) are thought not to affect cellular metabolism and may even exert a protective effect on enzymes (Greenway and Munns, 1980). Maintenance of favourable water relations is not without cost to the plant; frequently the metabolic energy that is diverted to the maintenance of tolerance results in a depression of growth (Stavarek and Rains, 1983).

There is a considerable amount of evidence that trees can make osmotic adjustments in response to salinity. For example, Spirig (1981) found decreased leaf osmotic potentials in salt damaged oak (*Quercus robur*), horse chestnut (*Aesculus hippocastanum*), lime (*Tilia × euchlora*) and London plane (*Platanus × hispanica*). Oak had the lowest osmotic potential and was the least injured of the four species. Pezeshki and Chambers (1986) found that the water potential (the product of osmotic potential and turgor pressure) of salinized ash (*Fraxinus pennsylvanica*) decreased with decreasing soil water potential, and Bongi and Loreto (1989) found that the osmotic potentials of salt stressed olive (*Olea europa*) trees were lower than the unsalted controls. Sucoff (1975) also found decreased osmotic potentials in needles of salt damaged red pine (*Pinus resinosa*) alongside roads in Minnesota.

On the other hand it appears that some plants may not be able to respond to decreasing osmotic potential of soil by decreasing internal osmotic potential. One example comes from the work of Leonardi and Flückiger (1985; 1986) who found that leaf water potentials of salt-stressed ash (*Fraxinus excelsior*) were higher (less negative) than the unsalted controls suggesting that osmotic adjustment had not taken place. Stomatal conductance was initially decreased, thus preventing excessive transpiration, but later in the season control of stomatal conductance, and hence of water loss, appeared to be impaired resulting in a rapid spread of leaf necrosis.

A further mechanism by which plants may be able to avoid osmotic stress is the ability to take up water preferentially from areas of the soil with the lowest salinity. West (1978a) exposed apple (*Malus sylvestris*) seedlings to a non-uniform salinity stress by using a split-root technique. One half of the roots were exposed to salt solution whilst the other half were immersed in water. He found that when salinity stress was applied to one root zone water uptake was decreased by about 50%, however, uptake by the non-stressed root zone compensated for this by increasing its water uptake by 50%. Overall water uptake was therefore unchanged.

Specific ion effects

The ions Na^+ and Cl^- may directly or indirectly affect plant growth when present in the soil or in plants at high concentrations. In contrast to osmotic effects where damage is the result of the overall potential of a saline solution, specific ion effects arise through the action of these particular ions on different soil and plant processes. The exact mechanisms of ion toxicity, however, are not known and this may be partly because many of the effects of Na^+ and Cl^- are indirect rather than direct, and because specific ion effects may be confused with osmotic effects. This problem is highlighted in a review of salt tolerance by Greenway and Munns (1980):

> For non-halophytes, we usually have no idea how the ions exert their adverse effects; this could be on membrane permeability or enzyme activity. Alternatively, high ion concentrations in the water of the cell walls could decrease turgor or volume. At present these effects cannot be distinguished experimentally.

Although the specific mechanisms of ion toxicity are not certain, it is clear from the evidence available that the chloride ion is the principal cause of injury in plants suffering from salt damage. The evidence for a primary role of Cl^- in salt injury is as follows.

1. In salt damaged plants Cl^- levels are always elevated.
2. Concentrations of Cl^- in leaf and shoot samples are almost always correlated with degree of injury but concentrations of Na^+ rarely are.
3. Concentrations of Cl^- are generally 2-3 times greater than concentrations of Na^+ in injured plants.

It appears that Cl^- is probably not directly toxic to plants but that it causes changes in plants which lead to decreased growth and eventually to visible injury. In salt contaminated soils, chloride is present in the soil at a greater concentration than other anions and is thus taken up by plants at a proportionally greater rate. As a consequence uptake of phosphate (Sands and Clarke, 1977), sulphate and nitrate (Poljakoff-Mayber, 1975) may all be decreased, and may even become deficient. It has been suggested that chloride-induced P deficiency was responsible for some of the damage observed in salt-affected *Pinus radiata* (Sands and Clarke, 1977). In addition to inducing anion deficiency it has been suggested that Cl^- may alter the ratios of different anions resulting in changes which impair cellular metabolism. According to Levitt (1972) chloride toxicity, rather than being proportional to the Cl^- concentration in plant tissue, is proportional to the $Cl^-:SO_4^{2-}$ ratio; thus, a decrease in SO_4^{2-} uptake will result in increased Cl^- injury.

Leonardi and Flückiger (1986) suggested that Cl^- induced ion imbalance may have been responsible for the stomatal closure and foliar injury in ash (*Fraxinus excelsior*) described earlier. Using X-ray analysis they found that Cl^- accumulated in large quantities in the vacuoles of stomatal guard cells. This increase in anionic content was accompanied by an increase in the concentrations of the cations Ca^{2+} and Mg^{2+} in guard and epidermal cells, ions which are known to be involved in stomatal closure. Leonardi and Flückiger suggested that stomatal closure was therefore caused by a Cl^- induced excess accumulation of Ca^{2+} and Mg^{2+} in guard and epidermal cells, and perhaps also in cell walls, which impaired normal electrolyte transfer in the epidermis thereby injuring the stomatal apparatus. They suggested that marginal necrosis of leaves was caused by elevated leaf temperature, resulting from decreased transpiration, which was accentuated in the middle of summer when ambient temperatures were at their highest.

Bernstein (1975) suggests that hormone balance may be affected by salinity and cites two studies which indicate that high levels of chloride decreased transport of kinetin from roots to shoots and increased leaf abscisic acid content. Both of these changes decrease stomatal aperture. He also suggests that enzyme activities may be altered by high Cl^- concentration, the activity of the enzymes malate dehydrogenase and acetic thiokinase showing a marked reduction at high salt concentrations. Levitt (1972) has reviewed the information on salt toxicity and suggests that injury is caused by salt induced changes in several metabolic processes such as respiration, photosynthesis, protein synthesis and nucleic-acid synthesis. He also presents evidence that enzyme activity may be altered (increased or decreased), carbohydrate metabolism may be impaired and synthesis of chlorophyll and carotene may be decreased. The work of Stroganov (1964) is cited which shows that salt-induced growth reduction led to an increase of unused growth substances such as amino acids. Stroganov points out that some of these unused amino acids may be toxic. In particular it was found that putrescine concentrations increased in salt-affected plants. Putrescine is normally deaminated in the presence of diamine oxidase, with proline being the end product; injury due to accumulation of putrescine would therefore be the result of a salt-induced decrease in the activity of diamine oxidase, which has been shown to occur in cotton leaves. Potassium deficiency is one of the factors that has been shown to cause increased putrescine accumulation, thus, the interference of Na^+ in K^+ absorption by plants may be responsible for this effect in salt stressed plants.

Stroganov also found that leaves of salt-injured plants had increased peroxidase activity. This may have played a role in the oxidation of the accumulated metabolic substances, leading to the formation of melanin from tyrosine in the necrotic areas. Catalase activity was also increased indicating a toxic accumulation of hydrogen peroxide. Toxic chlorine-containing substances were also found in the salinized plants.

Although the damage to plants from salt is caused mainly by the effects of toxic concentrations of ions within cells, these ions may have harmful effects even before they come into contact with plants. Sodium in high concentrations is particularly damaging to the soil as it decreases fertility and increases compaction (Bernstein, 1975). Positively charged ions (cations) are held in the soil on what are called 'cation exchange sites'; the proportion of different cations on these sites being determined by their charge and concentration. Thus as the proportion of exchangeable Na^+ in the soil increases the proportion of other exchangeable ions of greater nutritional importance, such as Ca^{2+}, Mg^{2+} and K^+, decreases. The ions that are displaced from the cation exchange sites are therefore lost from the soil by leaching, with the end result that soils become nutritionally deficient. This is a well known phenomenon for saline agricultural soils (e.g. Heikal, 1977) but has also been shown to occur for roadside soils affected by de-icing salt (Fleck *et al.*, 1988; Hofstra and Smith, 1984). Besides impoverishing the soil, elevated levels of sodium increase the soil pH to levels that are often inhibitory to plant growth, and cause a breakdown of the soil crumb structure, leading to soil compaction. The effects of soil compaction are well documented (e.g. Russell, 1973) and include waterlogging, drought, and lack of oxygen, all of which restrict plant growth. Furthermore, soil oxygen deficiency has been shown to increase Cl^- uptake. West (1978b) found that apple (*Malus sylvestris*) trees exposed to salinity and soil oxygen deficiency at the same time took up seven times more Cl^- than plants exposed to salinity alone.

Sodium causes further nutritional problems for plants because, as with chloride, it is taken up by plants at a proportionately greater rate than the other more important ions. Indeed, French (1959) has shown that, although calcium may be present in adequate quantities in the soil its uptake may be reduced by up to 40% in salt-affected soils. This type of effect has been shown to alter cation ratios in the plant. Low Ca^{2+} : Na^+ ratios can increase membrane permeabilities leading to an increase in passive Cl^- and Na^+ transport (Greenway and Munns, 1980). K^+: Na^+ ratios have also been shown to be decreased by salinity (Leonardi and Flückiger, 1986) and this can result in loss of control of membrane permeability and selectivity, with a consequent further increase of Na^+ and Cl^- uptake.

Separating osmotic and specific ion effects

As indicated above, osmotic and specific ion effects are closely linked and it is therefore difficult to determine the relative importance of each injury mechanism (Greenway and Munns, 1980). However, studies using isosmotic concentrations of different salts have given an indication of which effect is the more important. For example, Dirr (1975) applied sodium chloride (NaCl) or sodium sulphate (Na_2SO_4) at equal concentrations to the soil in which ivy (*Hedera helix*) plants were growing. He found that injury was more severe in plants supplied with sodium chloride than plants supplied with sodium sulphate, indicating, firstly, that Cl^- was the principal toxic ion, and secondly, because both salts were present in the soil at the same concentration (same osmotic potential), that the specific toxicity of Cl^- was more damaging than the osmotic stress. Sands and Clarke (1977) conducted a somewhat similar experiment growing *Pinus radiata* in isosmotic solutions of polyethylene glycol (PEG) and NaCl. PEG is generally thought to be non-phytotoxic and because of the size of the molecule is not readily taken up by roots. Thus any differences in the responses of plants grown in the two media would be attributable to specific ion toxicity.

Seedlings grown in PEG solution wilted, commencing from the top, as a result of 27 days of osmotic stress but recovered over the next 13 days after stress was released. In contrast, the injury observed in the plants grown in salt solution was permanent and different in nature. During the stress period plants became progressively more brittle and necrotic, and this continued even after the stress was released. This clearly indicates therefore that injury was largely due to specific ion effects rather than osmotic effects.

At present the general concensus of opinion is that the toxicity of specific ions, particularly Cl^-, accounts for a greater proportion of salt induced injury than osmotic stress (e.g. Dirr, 1974; Spirig, 1981).

Conclusions

When salt reaches the living parts of plants injury often results. Salt may enter the roots of plants and be transported to other plant parts, or may enter the shoots when salt is aerially applied. The sites of salt entry into shoots are not certain. Salt may cause osmotic stress in the roots resulting in reduced water uptake, although the evidence for this is equivocal. Plants are often able to adapt to osmotic stress by altering their internal osmotic potential. It appears that the toxicity of specific ions is responsible for a greater proportion of salt induced injury than osmotic stress. Sodium and chloride cause injury by affecting soil structure and fertility, by causing nutrient imbalance in plants, and by altering cell physiology and function. Altered metabolism, altered hormonal balance, and impaired stomatal control may all be involved in the process leading to plant injury.

Chapter 4

An Evaluation of the Methods for Reducing Salt Damage

Introduction

The damage caused by de-icing salt is an environmental problem which, unlike many others, is clearly capable of solution. There are four options for reducing damage to existing trees. The first is to reduce the use of de-icing salt. This may be achieved by restricting its use and by exercising greater care over its use through more efficient storage and application techniques. The second is to use alternatives to salt which are less damaging to the environment. The third option is to apply materials that will ameliorate the effects of salt, and the fourth is to reduce the amount of salt reaching trees through design solutions. All these approaches are considered here. A fifth approach to the problem, that of planting salt tolerant species, has already been considered in some depth (Chapter 2).

Reducing use of salt

Methods of curtailing the use of salt have been comprehensively reviewed in two recently published reports, the first on a national scale (Audit Commission, 1988) and the second on an international scale (OECD, 1989). The main findings of these and other related publications are outlined below. The striking conclusion of the Audit Commission is that local authorities in England and Wales waste up to 60% of all the salt they buy each year (with a value of up to £21 million) through inadequate storage and inaccurate spreading. It follows therefore that if correct procedures for the handling of salt were adopted the amount of salt used annually in this country could be substantially decreased without any reduction in road safety.

Salt storage

In Britain salt is generally stored in the open. This causes two problems. Firstly, rainfall leaches the salt away at a rate calculated by the Transport and Road Research Laboratory (TRRL) to be equivalent to approximately 0.25% of the total stockpile per inch of rainfall per year (cited by Audit Commission, 1988). Taking the average annual rainfall in the UK to be 30 inches, in 1986 the total loss of salt was in the region of 188 000 tonnes, at a value of £3.6 million. As well as being wasteful, salt leached in this way causes local soil pollution, evidenced by the fact that salt stockpiles are frequently surrounded by dead vegetation, including trees (Plate 13). The second problem is that moisture from rainfall causes the salt to coagulate, and because the spreading mechanism on distribution vehicles is not designed to spread coagulated material, overspreading results. The TRRL has calculated that this overspreading can be of the order of 18% by volume, and in 1986 this was equivalent to 450 000 tonnes of salt at a cost of up to £8.7 million (Audit Commission, 1988).

To prevent wastage of this nature salt can be stored in the open under polythene sheeting or can be kept in specially designed barns or silos. The use of polythene sheeting has not found favour with some local authorities because of handling difficulties in windy conditions and because staff dislike having to cover and uncover stockpiles in inclement weather. Nevertheless, the Audit Commission quoted one county that covered 3000 tonnes of salt at a cost over five years of £5000. The savings made during this period amounted to approximately £13 000. The other alternative, building storage facilities, inevitably incurs a greater capital cost and consequently longer payback periods. However, the Audit Commission was shown some relatively simple, but completely adequate, wooden structures which had a payback period of only 3 years.

Damage to trees is frequently caused by the inappropriate siting of roadside salt stores for the use of motorists and pedestrians. It is not uncommon for unprotected piles of salt to be placed under the crowns of trees, with subsequent severe dieback or mortality resulting (Plate 11). Even when salt is stored in weatherproof containers, these may be sited so close to trees that damage is almost inevitable when the salt is used (Plate 12). These problems could be minimised if salt was stored in weatherproof receptacles situated well away from any trees.

Salt spreading

According to Department of Transport guidelines (Department of Transport, 1987) salt should be applied to roads at a rate of between 10–40 g m^{-2}. For precautionary salting prior to a frost salt should be applied at 10 g m^{-2} (Plate 1), while if freezing conditions after rainfall or continuous snow are expected, the recommended rate is 20–40 g m^{-2}. There are no advantages in spreading at any rate above 40 g m^{-2}. In spite of this, data collected by the Audit Commission show that in practice local authorities spread salt at an average rate of between 20–83 g m^{-2}. Part of this overspreading is caused by the problems of coagulation described above. Another contributory factor is the inefficiency of the salting procedure. In addition to purpose built salt-spreading vehicles many winter maintenance fleets comprise an assortment of vehicles such as converted refuse freighters and ex-army lorries, the carrying capacity of which may bear little resemblance to the workload (Audit Commission, 1988). The Audit Commission reports that overspreading often results from the use of fully loaded large lorries to salt relatively short stretches of roadway. A more important cause of overspreading, however, is the failure to calibrate the spreader mechanisms on vehicles for volume dispensed and width of spread. Calibration can be achieved relatively simply and should be performed at least once during each winter maintenance season. Furthermore, the majority of equipment spreads salt at a preset rate regardless of vehicle speed. As a result proportionally more salt is spread per unit area at slower speeds, and excessive amounts are spread at road junctions or traffic lights when vehicles are stationary. The TRRL are currently investigating methods for relating rate of spread to vehicle speed.

Overlap between the spreading routes of different vehicles and two way spreading also contribute to oversalting. Planning of routes to minimise overlap, and salting both carriageways on one pass rather than two, could both save salt (Audit Commission, 1988). In addition, further savings in salt could be made by adopting European spreading patterns, such as wet salt spreading (see below), and setting the width of spread to 2 metres less than the width of the carriageway. Although this means that one metre on each side of the carriageway is not initially salted, the subsequent action of passing traffic spreads the salt to the road edges. Adopting European spreading practices and ensuring correct calibration of equipment could reduce salt consumption by up to 25% with an annual saving in the region of £10 million per year in England and Wales (Audit Commission, 1988).

A major cause of damage to trees is the salting of pathways and pedestrian precincts. In such areas salting is usually carried out by hand, which is considerably less controlled than spreading from salting vehicles, and the quantities of salt used are invariably far in excess of that required. Significant dieback and mortality occur in such locations even during relatively mild winters; this being particularly noticeable in pedestrian precincts. The use of hand operated mechanical spreaders which allow controlled accurate spreading could help to minimise such problems. Appropriate design of pedestrian areas so that salty water does not flow directly into the rooting area of trees would also be beneficial (see 'Amelioration through design and engineering', p. 54).

Wet salt spreading

The differences in climate and types of salt used in countries which experience temperatures below zero have given us three distinct spreading techniques (OECD, 1989). These techniques have been given particular names in Germany and so the description below uses their nomenclature. FS stands for *Feucht Salz* (moist salt).

The first method, that of dry salt spreading, is where salt is delivered with a very low moisture content and is stored under cover. Salt is thus spread in a very dry form. This technique was used widely in Germany in the 1970s. However, because dry salt was easily blown away during and after spreading the potential of using moist salt was investigated. The resulting 'FS5' technique involves spreading salt with a moisture content of 5%. This figure is usually achieved by spraying sodium or calcium chloride solution on to the salt as it is being loaded into the vehicle's hopper. Because the fine particles of salt are thus bound together during spreading they are less easily blown away. In addition, thawing begins up to 15 minutes earlier than if dry salt is used (OECD, 1989). Most salt in Britain comes from the ICI mine in Cheshire and after storage in the open has a relatively uniform moisture content of about 5%. Using this salt can therefore give the same benefits as using the FS5 technique. However, storing salt in the open incurs losses as described earlier. If, as recommended above, ICI salt were to be stored under cover the FS5 technique would become more relevant. Some counties in the UK use dry, imported, salt and therefore adopting the FS5 technique in these areas would undoubtedly prove beneficial.

Another technique developed in Germany is known as 'FS30'. With this procedure a specially designed vehicle simultaneously spreads solid salt and sprays brine (usually a $CaCl_2$ solution) at a concentration of 16–33%. The 30 in FS30 represents the proportion (30%) of the total that is spread in liquid form. The advantages this has over the FS5 technique are that better adhesion is achieved, thawing occurs more rapidly, and there is greater flexibility in regulating the rate of spread as required by the road conditions (OECD, 1989). The drawback of this method, however, is that spreading vehicles must be equipped with an additional tank to carry the solution. Conversion costs may nevertheless be offset against the savings brought about by the reduction in use of salt which has been estimated to be in the order of 50% (OECD, 1989) compared to dry salt spreading, and possibly by a reduction in the number of vehicles needed due to the quicker speeds of operation (up to 70 km h^{-1}; OECD, 1989). The first set of trials for the FS30 technique were planned by the UK Department of Transport for the winter of 1987–88 under the guidance of the TRRL. However, the mildness of that winter meant that no useful results were obtained, and the same was true of the following two winters.

Ice prediction systems

In Britain ground frosts occur on average between 40–90 days of the year, are generally shortlived, and occur irregularly principally between November and March. British winters thus cause problems for the winter maintenance engineer not only because of the frequency of frosts at or just below 0°C (ice is at its most slippery at 0°C; OECD, 1989) but also because of the difficulty encountered in making the decision of when to salt. Until relatively recently engineers had to base their decisions on general regional weather forecasts and local observations of weather and road conditions. This imprecise method of estimating road condition often resulted in an erratic service to the road-user with some icy roads remaining unsalted whilst others were salted unnecessarily. As winter maintenance engineers have tended to err on the side of caution the latter situation has arisen more frequently than the former resulting in a considerable wastage of salt. Improved accuracy of ice prediction could thus minimise unnecessary salting.

Vaisala TMI in conjunction with the Department of Transport and the Meteorological Office have recently developed the idea of a National Ice Prediction System (Figure 4.1). It was due to this cooperation that in 1986 the Meteorological Office was able to introduce its new commercial ice prediction service called

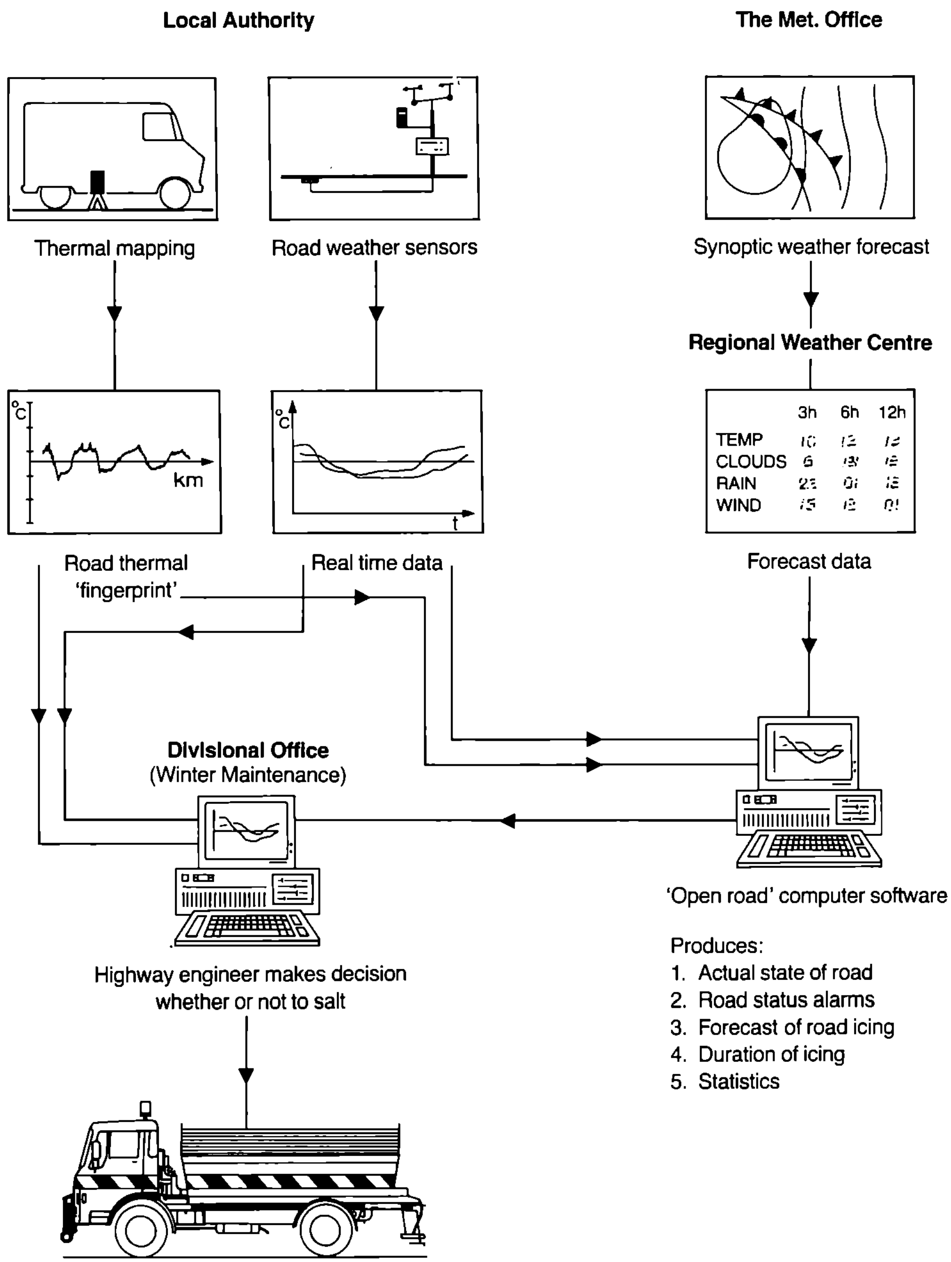

Figure 4.1 Schematic diagram illustrating the relationships between the different components of the UK National Ice Prediction System.

Open Road. This service is provided to counties/regions by each of the 14 regional Weather Centres. At the heart of *Open Road* is an ice prediction model, developed by the Meteorological Office and run on microcomputers at each Weather Centre. This combines traditional synoptic weather forecasts (wind speed, cloud cover, air temperature, dewpoint and rainfall), data from roadside ice detection equipment located at various points on the road system which monitor air temperature, road surface temperature, sub-surface temperature, humidity, surface moisture and residual salt (see below), and local forecaster knowledge to produce site-specific forecasts of overnight road surface temperatures which may lead to icy conditions. The forecasts are usually issued at midday (although they can be made up to 5 days ahead) and are transmitted to divisional offices via facsimile or computer link. Forecasts are generally only updated thereafter if prediction of the frost–no frost situation alters appreciably. The forecasts are specific to each sensor site and give information on whether or not the road temperature at that location will fall below freezing, at what time and for how long the temperature will remain below freezing, and whether the road surface will be wet when the temperature falls below freezing. The winter maintenance engineer uses the forecast and actual data from each sensor site, plus his expertise, to decide whether and where to salt.

Although *Open Road* may be used without roadside ice detection systems, a greater degree of accuracy is achieved if these are installed. The number of sensors needed adequately to cover a road network is based on having one site per 256 km^2 (Thornes, 1989). The siting of these sensors requires careful consideration of factors such as topography, traffic density, exposure and altitude which affect road micro climate. For instance, placing sensors only at cold spots gives the impression that a region is colder than it really is.

'Thermal mapping' is the technique that has been used to map these variations in road temperature so that suitable sites can be located. Thermal mapping is undertaken using an infrared thermometer mounted on the back of a vehicle. A particular section of road is mapped at night on up to five different occasions with different weather conditions. This gives a 'thermal fingerprint' for that particular section of road which shows which are the consistently cold parts of the road and which are the relatively warm sections. As well as assisting in the selection of sensor sites this map enables the interpolation of surface temperatures on particular sections of road from the forecast data for a nearby sensor site. Thermal mapping may thus allow salting routes to be replanned as 'cold', 'warm' and 'intermediate' routes. This would mean that on certain nights only cold routes might need to be salted, with a consequent saving in salt.

A useful feature of roadside ice detection systems is the capacity to estimate the amount of de-icing salt remaining on the road from a previous salting operation (residual salt). If sufficient residual salt is present resalting is unnecessary and both time and salt can be saved. The amount of residual salt is estimated by measuring the conductivity between two electrodes placed in the road. It has been shown that as little as 3 g m^{-2} is sufficient to make resalting unnecessary and this is equivalent to a conductivity of about 100μS (OECD, 1989). On a moist road the conductivity after salt spreading is in the range 200–600μS, conductivity increasing with both amount of salt and moisture. During a sunny day conductivity decreases to zero as the salt dries out but increases again during the evening due to the hygroscopic nature of salt and the humidity in the air. Values of below 100μS are difficult to interpret; either there is insufficient residual salt or insufficient moisture to dissolve the salt. In this case it is necessary to combine conductivity measurements with data on the humidity of the air and the amount of precipitation to find out the actual amount of residual salt.

At the start of the 1988–89 winter the thermal mapping of more than 21 000 km of roadway in 45 UK highway authority areas had been undertaken. Approximately 320 road weather outstations had been installed in 30 counties or regions and over 50 were using the *Open Road* service (Thornes, 1989). This has involved an investment in the region of £5 million compared with a cost of about £100 million for providing de-icing services in England and Wales during an average winter. Using sensor data it has been possible to check the accuracy of *Open Road* forecasts and the Meteorological Office have found that the frost–no frost situation has been correctly predicted 85–87% of the time. Using this service can give savings in salt of the order of 25–30%.

Alternatives

Despite its cheapness (approx £25 per tonne) and effectiveness it has been estimated that the real cost of using salt, taking into account repairs to roads and bridges, vehicle corrosion, water pollution and damage to vegetation, is 10–15 times the purchase price (Dunn and Schenk, 1979; Murray and Ernst, 1976). This makes alternatives to salt which have a greater purchase price but are less environmentally damaging more economically acceptable than would otherwise be the case.

Roadway heating systems

Up to the mid-1970s roadway heating was achieved by burying electrical resistance cables beneath the road surface, but the energy costs for this type of heating were very high. Subsequently heat exchange systems were developed using heat from the soil, water or sewage systems. These too have proved very costly being in the region of £100–170 per m^2 of road to install (OECD, 1989). Technically such systems appear to be a good alternative to using de-icing chemicals but in practice the expense and difficulties encountered in installing and maintaining them have meant that their application has been very limited. Two tunnels in Switzerland have had roadway heating installed at their southern entrances, the St Gothard tunnel with a total heated length of 200 m (area of 1500 m^2) and the Lopper tunnel with a total heated length of 60 m (area of 500 m^2). The running costs for the Lopper tunnel system are approximately £1400 per year, obviously too expensive for large-scale application.

Abrasives

The spreading of abrasives such as sand and crushed rock to improve traction under winter conditions began with the advent of metalled roads at the turn of the century (Driver, 1979). After the Second World War grit was largely replaced by salt, but recently growing awareness of the environmental damage caused by salt has promoted calls for a return to the use of abrasives, particularly in Germany (see OECD, 1989). It is therefore appropriate to consider the advantages and disadvantages of this particular form of winter maintenance.

The advantages of abrasives are that they are cheap (approximately £5 per tonne), widely available, and have little or no effect on roadside flora and fauna. They are, however, relatively ineffective in combating the effects of ice and snow in comparison to salt. The sideways force coefficient (*sfc*) of untreated ice is around 0.20. This may be increased to about 0.35 by applying crushed quarry rock and to about 0.4 by using fine sand (Driver, 1979). By contrast, *sfc*'s of up to 0.8 can be obtained when salt is used because it melts the ice. For grit to be effective large quantities have to be applied; typically 70–300 g m^{-2} in contrast to the 10–40 g m^{-2} required for salt. In addition, applications often have to be repeated several times a day because the grit is rapidly dispersed to the edges of the road by traffic (OECD, 1989). Thus, large quantities of grit build up in gutters and have to be cleared either during or after the winter maintenance season to prevent blockage of drains. Abrasives have a scouring effect on vehicle bodies which exposes metal to general corrosion, and there is also the danger that oversize stones may be used with the consequent risk of windscreen damage and danger to pedestrians and cyclists. The relative ineffectiveness of abrasives also leads to higher incidence of vehicle accidents than when salt is used (OECD, 1989). From a safety viewpoint, therefore, it is difficult to justify the use of abrasives as an alternative to salt. Added to the increased potential for loss of life is the financial cost of increased incidence of accidents; a single fatality on the roads incurs costs in the region of £1 million. Furthermore, it has been estimated that if all the expenses involved in using abrasives are added up, including delays to traffic, the overall cost can be four to seven times that of salt (Driver, 1979).

Despite the factors outlined above, in West Berlin concern over the damage to street trees caused by de-icing salt resulted in a change of winter maintenance policy in the late 1970s. In 1975 salt was banned from pavements and side streets, and the maximum single dose was reduced to 40 g m^{-2} and three applications per 24 h. In 1979 the maximum dose was again reduced, to 20 g m^{-2}, and in 1981 the use of salt was restricted to dangerous stretches of a few main roads. Grit has been used in place of salt. Balder (1988) studied the health of Berlin's street trees during 1971–1976 and in 1987, and found that the change of winter maintenance procedures had resulted in a reduction in the incidence of leaf necrosis characteristic of salt damage and a reduction in foliar and soil levels of sodium and chloride.

Salt/abrasive mixtures

Because of the limited effectiveness of using abrasives on their own it has been suggested that salt/abrasive mixtures should be used. However, no critical studies have been conducted to determine whether this would be a valid way of reducing salt usage. The OECD (1989) describe the situation in some German cities, which over the last decade have used such mixtures. Data show that the mixture is spread at an average rate of about 60 g m^{-2}, the proportions of salt used ranging from about 10–90%, with 30% being the most frequently reported rate. Based on these values it can be calculated that the amount of salt actually applied to the roads is on average about 15 g m^{-2}, equivalent to or slightly less than the pure salt technique. However, salt/grit applications tend to be repeated more frequently than applications of pure salt and this results in greater quantities of salt being used than if salt was used alone. A similar situation has been recorded in the USA (Fromm, 1982). Further investigations are needed to ascertain whether the use of salt/grit mixtures has real potential for reducing salt consumption.

Chemical de-icing agents

De-icing chemicals have their effect by depressing the freezing point of water. The degree to which the freezing point is lowered depends almost entirely on the number of solute ions in solution, and is independent of the nature, size or weight of these particles (Dunn and Schenk, 1980). Thus, for a given weight, materials of low molecular weight and high solubility produce the greatest lowering of the freezing point because they liberate the highest number of ions into solution. In order to find effective alternatives to NaCl then the search must be for chemicals of low molecular weight and high solubility. They should also be reasonably cheap to buy or manufacture, persistent when applied, and cause less damage than salt to bridge decks, road surfaces, vehicles and vegetation. These criteria are extremely difficult to fulfil but a number of possible alternatives are considered below.

Inorganic de-icing agents

Chlorides

The chlorides are all very efficient as de-icing agents. $CaCl_2$, $MgCl_2$, and KCl are therefore all potential alternatives to NaCl. $CaCl_2$ is the strongest competitor with NaCl, and indeed comprises 5% of the de-icing salts used in North America and parts of Europe (Krapfenbauer, 1976). In Italy and Belgium $CaCl_2$ constitutes about 20–25% of all de-icing agents used (OECD, 1989). The eutectic point (the lowest freezing point that can be achieved by dissolving a particular chemical in water) of $CaCl_2$ is –51.6°C, lower than that of NaCl (–21.1°C). Its de-icing qualities are as good as those of NaCl down to temperatures of –10°C and between –10 to –20°C appreciably better (Krapfenbauer, 1976). $CaCl_2$ has a rapid initial thawing effect because the dissolving of $CaCl_2$ in water is exothermic and contributes 14 cal/g to the melting process (energy equal to 80 cal/g is required to melt snow or ice; Krapfenbauer, 1976). The dissolving of NaCl is an endothermic reaction and requires 6.1 cal/g of heat which is drawn from the surrounding area. $CaCl_2$ is currently only used in relatively small quantities because temperatures during winter precipitation in Europe rarely fall below –4°C and for this NaCl is sufficiently effective. However, the use of $CaCl_2$ may be better in terms of reducing tree damage because less needs to be used for the same thawing effect, and the only damaging component is the Cl^- ion.

Opinion has been divided as to whether NaCl or $CaCl_2$ has the more damaging effects on roadside vegetation. For example, Walton (1969) emphasised the greater harm of $CaCl_2$ to Norway maple whereas Westing (1969) and Rich (1971) pointed out that in general NaCl is the more toxic to vegetation. Several recent studies have attempted to resolve these contradictions by comparing the phytotoxicity of NaCl and $CaCl_2$ on young trees. Some authors (e.g. Sands and Clarke, 1977; Sury and Flückiger, 1983) have treated plants with solutions of equal osmotic concentration whereas others have used solutions with equal numbers of chloride ions (e.g. Bogemans *et al.*, 1989 a and b). The former have found $CaCl_2$ to be more phytotoxic to trees than NaCl because solutions of $CaCl_2$ contain 1.33 times more Cl^- ions than isosmotic solutions of NaCl. It was thus that Sands and Clarke (1977) found that Monterey pine (*Pinus radiata*) treated with $CaCl_2$ had 34% more Cl^- in the needles and exhibited significantly greater damage than trees treated with an isosmotic solution of NaCl. In the latter situation Bogemans *et al.* (1989 a and b) found that Norway spruce (*Picea abies*) growing in pots or in field plots treated with solutions of NaCl and $CaCl_2$ containing equal numbers of Cl^- ions showed decreased Cl^- and Na^+ accumulation in the tissue in the $CaCl_2$ treated plants. The replacement of 20–30% NaCl by $CaCl_2$ resulted in a 50% lower Na^+ concentration and a 25% decrease in Cl^- concentration in the needles. The addition of Ca^{2+} also enhanced leaching of Na^+ from the soil of the field plots. Using solutions of equal numbers of ions is more representative of the field situation and thus it seems that $CaCl_2$ is probably less damaging than NaCl. However, more work is necessary to clarify the responses of plants to mixtures of these two salts.

The disadvantages of $CaCl_2$ are that it is about 2–3 times more expensive than NaCl and that it is highly hygroscopic which can cause storage and handling problems. In addition, although it may be less damaging than NaCl, $CaCl_2$ can still cause considerable damage to trees, and corrosion to vehicles and bridges.

The eutectic point of $MgCl_2$ is –33°C. Nevertheless, because of its extreme hygroscopicity it could only be used as a de-icing agent in a dissolved form and would therefore be inappropriate for use with existing machinery. In addition it is more expensive than NaCl and is particularly corrosive so its potential as an alternative de-icer is limited (OECD, 1989). Similar problems apply to KCl.

Sulphates

$(NH_4)_2SO_4$ and $MgSO_4$ have an excellent thawing capacity but are not considered suitable for use on roads because of their effect on concrete (Krapfenbauer, 1976). Almost all roads have certain parts that are made with concrete or are bound by cement mortar. The damage from sulphate is connected with the formation of calcium-sulphur-aluminate that destroys concrete by raising its volume on crystalisation. $(NH_4)_2SO_4$ is also unsuitable due to its high nitrogen content which may cause over-fertilisation of trees and surface and groundwater pollution.

Urea

Urea is currently used to a limited extent on airport runways and on bridges because it is non-corrosive. Its use is restricted, however, because of its high cost (£160 compared with £25 for NaCl) and because of its limited effectiveness. The eutectic point of urea is –12°C, poorer than that of NaCl, and its de-icing capability drops sharply at temperatures below –7°C (OECD, 1989). As urea is very light it is easily blown away and so is invariably spread in a mixture by volume of 7 parts urea to 1 part wetting agent (which consists of 3 parts water to 1 part anti-freeze, usually ethylene glycol; Department of Transport, 1987). Urea is used in this country on some long sections of elevated carriageway and on some bridges, e.g. the Severn, Wye and Avon bridge complexes. The average annual usage on the Severn bridge since it opened in 1966 has been about 40 tons (Driver, 1979). Urea can make roadside soils less suitable for plant growth by depleting soil oxygen as it is decomposed, and may cause overfertilisation of roadside vegetation which could decrease frost resistance. Its decomposition product, ammonia, is toxic to aquatic life.

Organic de-icing agents

Alcohols and glycols

Isopropyl alcohol and ethylene glycol are used routinely on airport runways and taxiways because of their non-corrosive properties. However, even when large quantities are used they thaw effectively only to temperatures of about –5°C, and they are considerably more expensive than salt (Krapfenbauer, 1976). Isopropyl alcohol reduces the surface tension of the melt water and as a result allows it to penetrate the fine cracks in the runway surface. Once the alcohol has evaporated, the freeze-thaw action of the remaining water can cause parts of the surface to crack and spall off (OECD, 1989). A major disadvantage of these and other organic de-icers is the high oxygen demand for their decomposition. Surface water contains up to 14 mg of O_2 per litre, thus for the decomposition of 1 kg of organic de-icing agent with an O_2 requirement of 100% of its weight, the O_2 content of approximately 70–100 m^3 of water would be needed (Carlier and Snoeck, 1974). If alcohols and glycols were used on roads severe O_2 depletion in rivers and streams receiving runoff would be expected (Krapfenbauer, 1976). Their effects on vegetation are not known.

Methanol

Owing to concerns over the environmental damage caused by the use of NaCl in highway de-icing, the US Department of Transport commissioned a research programme in the late 1970s to identify non-toxic and non-corrosive alternatives to salt. The subsequent report by Dunn and Schenk (1980) identified methanol as a potential alternative. It is non-toxic, non-corrosive, and its decomposition products are water and carbon dioxide. The eutectic point of methanol is –120°C, far below that of NaCl or any other inorganic de-icer. At temperatures above –15°C the performance of methanol is comparable to that of NaCl, however, because of its volatility greater quantities may have to be used. The methods for dispensing liquids such as methanol are much simpler than for solids and are subject to much finer control. Methanol does not corrode metal or affect cement or concrete and although its effects on vegetation have not been assessed they are likely to be of minor significance. There are some concerns about methanol's flammability, but once applied to a frozen or snow-covered road, it appears to be difficult, if not impossible to ignite (Dunn and Schenk, 1980). Its principal disadvantage is that it may increase biological oxygen demand (BOD), however, this effect is reduced by its volatility. Although the purchase price is higher than that of salt the total costs including purchase, application and environmental damage are likely to be considerably less than those associated with salt (Dunn and Schenk, 1980).

Calcium magnesium acetate

Calcium magnesium acetate (CMA) was also identified as a potential alternative de-icer by Dunn and Schenk (1980). The eutectic point of solutions of the two main components of CMA, calcium and magnesium acetates, are –15°C and –30°C respectively, giving an average of –21°C, similar to that of NaCl. In equal osmotic concentrations the de-icing capabilities of CMA and NaCl are comparable, taking the same amount of time to have their initial effect and having similar persistence (Dunn and Schenk, 1980). However, on a weight basis, slightly more CMA is required to achieve the same level of thawing. CMA is less corrosive to steel than NaCl being comparable to or less corrosive than tap water. Damage to structural concrete is negligible. The main disadvantage of CMA is its purchase price which is about 20 times that of salt.

Once CMA had been identified as a possible alternative to salt the US Federal Highway Administration (FHWA) sponsored research to ascertain its effects on water, soil and vegetation. Two studies were carried out, the first by the California State Department of Transportation (Winters *et al.*, 1985) and the second by the University of Washington (Horner, 1988). It was found that soils treated with 5000 ppm CMA had higher permeability than controls; an effect which was explained by the creation of more pore space following particle flocculation caused by the Ca and Mg (Horner, 1988). The environmental consequence of CMA of most concern was that of increased BOD. The findings of Horner (1988) prompted the following recommendations.

1. CMA should not be applied in catchments when less than 100 fold dilution will be available in waters receiving direct runoff. This guideline holds particularly in waters inhabited by aquatic species, of which salmonoid fish are the most sensitive.
2. Extra precautions should be taken when the temperature of the receiving water is starting to warm up. (A concentration of 10 mg l^{-1} completely depleted oxygen in 20 days at 20°C. The reaction rate was halved at 10°C.)

The study by Winters *et al.* (1985) compared the effects of CMA and salt on young potted individuals of 16 different tree and shrub species (Table 4.1). The trees were either sprayed with CMA or NaCl (at concentrations of up to 150 000 ppm) or had solutions of these chemicals added to the soil. For the plant irrigation treatments, nine species were more severely damaged by salt and one species (*Elaeagnus angustifolia*) was more severely damaged by CMA.

Work on the phytotoxicity of CMA has also been conducted by Horner (1988) on a variety of herbaceous and woody species. Young Douglas fir (*Pseudotsuga menzeisii*), red alder (*Alnus rubra*), balsam fir (*Abies balsamifera*) and red maple (*Acer rubrum*) were tested in the field and showed no signs of visible injury or stress. Work sponsored by the Austrian Federal Ministry for Construction and Technology (Waschuttl, no date) demonstrated favourable effects of CMA relative to NaCl on wheat, rape and cress grown in pots. No adverse symptoms appeared in field grown spruce, pine, maple or

Table 4.1 A comparison of damage caused to 16 tree and shrub species by soil or spray applied CMA and NaCl. Applications were made to the soil on five occasions between February and June 1982. Spray applications were made on four occasions between February and May 1982. (Reproduced from data presented by Winters *et al.*, 1985.)

	Calcium magnesium acetate (CMA)		***Sodium chloride (NaCl)***	
Species	*Soil*	*Spray*	*Soil*	*Spray*
Abies concolor (white fir)	1	1	3	3
Acer saccharum (sugar maple)	1	1	2	2
Amelanchier canadensis (June berry)	1	1	3	3
Betula papyrifera (paperbark birch)	0–1	0–1	2–3	2–3
Calocedrus decurrens (incense cedar)	1	1	2	2
Cornus florida (flowering dogwood)	2	0	3	3
Elaeagnus angustifolia (Russian olive)	3	2	1–2	2
Fraxinus pennsylvanica (white ash)	1	1	2	2
Malus 'Hopa' (flowering crab)	2	1	2	3
Pinus jefferyi (Jeffery pine)	1	0	3	3
Pinus lambertiana (sugar pine)	1	1	3	3
Quercus alba (white oak)	1–2	1–2	2–3	2–3
Quercus rubra (red oak)	1–2	1–2	3	3
Salix sp. (willow)	0	0	0	0
Thuja occidentalis (American arborvitae)	1	1	2	2
Viburnum lantana (wayfaring tree)	1	1	3	3

0 = 0% treatment related damage
1 = 1–25% treatment related damage
2 = 26–75% treatment related damage
3 = 76–100% treatment related damage

salt-tolerant shrubs with applications of CMA at rates of 60–100 g m^{-2}.

Limited work conducted by the Forestry Commission, and part funded by BP Chemicals Ltd. during the 1989–90 winter has also shown that CMA is less damaging to a range of tree species than NaCl (Dobson, unpublished). Young trees (1–4 years old) of Norway maple (*Acer platanoides*), hawthorn (*Crataegus monogyna*), ash (*Fraxinus excelsior*), English oak (*Quercus robur*), small-leaved lime (*Tilia cordata*) and cherry (*Prunus avium*) were potted into a 50:50 mixture of sand and peat and were subsequently treated with solutions of NaCl or CMA. Applications at concentrations of up to 60 000 ppm were made to the soil during February 1990. The cumulative doses were equivalent to up to 5 kg m^{-2}. High concentrations of NaCl delayed flushing to some degree in all species, and the highest concentration killed all the buds of *F. excelsior* and *T. cordata*. On the other hand CMA only delayed flushing in *A. platanoides*, *C. monogyna*, *F. excelsior* and *T. cordata*, and this effect was less pronounced than for salt. The appearance of the trees, scored on a scale of 1–5 (Lumis *et al.*, 1976), was assessed in August. The condition of all the species tested deteriorated sharply with increasing NaCl concentration. However, trees treated with CMA showed only minor damage even at the highest concentration, and *Q. robur* and *P. avium* were completely unaffected.

The rather limited soil studies conducted by Winters *et al.* (1985) indicated that a 0.5 M solution of CMA can potentially remove significant amounts of Fe, Al, Na, K and hydrolyzable orthophosphate from the soil. As a sequel to this Elliot and Linn (1987) performed batch and column experiments designed to investigate the Cu and Zn mobility of soils amended with CMA. In acidified soil columns CMA initially increased Cu and Zn efflux because preferential adsorption of Ca and Mg at cation exchange sites displaced bound metal ions into solution and desorbed H^+, thus acidifying the soil and releasing additional ions. Horner (1988) also found that Cu, Zn and Al were desorbed from cation exchange sites by CMA. Elliot and Linn (1987) discovered, however, that loss of ions was counteracted by the pH neutralising effect of the acetate so that there was eventually a net suppression of Cu and Zn loss. They speculated that CMA would temporarily increase the mobility of heavy metals but that sustained use would inhibit it.

CMA appears to be the least environmentally damaging alternative to salt currently available. Due to its high purchase price it is unlikely to replace salt as the predominant de-icing chemical but where the use of salt causes serious corrosion or environmental problems it is possible that CMA may find a use. Examples could include urban areas with high value amenity trees near to busy roads.

Amelioration

Amelioration through anti-transpirants

Tests have been conducted with various tree species to determine whether anti-transpirants can reduce salt spray injury. There are two types of anti-transpirant, those that close the stomata and those that coat the plant surface with a film of wax (Smith, 1971). The second type has been used to see whether it can prevent Cl^- ions from penetrating needles, shoots and buds. Reisch (1970) found that the anti-transpirants 'Vapour Gard' and 'Foli-Gard' reduced needle browning on white pine (*Pinus strobus*) and Norway spruce (*Picea abies*) sprayed with sodium chloride. On the other hand Emmons *et al.* (1976) sprayed six species in roadside plots in Minnesota (*Pinus nigra*, *Juniperus chinensis*, *Fraxinus pennsylvanica*, *Cornus stolonifera*, *Syringa vulgaris* and *Malus* var. *radiant*) with 'Vapour Gard' (a pinolene) and 'Wilt Pruf' (a beta pinene) and found that there was no reduction in twig dieback on the deciduous species and increased needle damage on *P. nigra*. 'Wilt Pruf' also resulted in heavy needle mortality on *Juniperus chinensis*. Constantini and Rich (1973) found that seedlings of *Pinus strobus*, *P. sylvestris*, *Picea glauca* and *Abies fraseri* sprayed with salt and an anti-transpirant had slightly higher chloride concentrations in the needles than trees receiving salt spray and no anti-transpirant. In Germany Sauer (1980) tested several types of anti-transpirant but found that none of them were effective in protecting roadside plants from salt spray injury. It seems therefore that anti-transpirants are not a promising way of reducing damage from traffic spray containing de-icing salt.

Amelioration through watering

A simple and effective way of dealing with soil salt contamination is to flush the soil with large volumes of water (Rich, 1972; Shaw and Hodson, 1981; Tomar and Gupta, 1985). Chloride ions, being anionic, are repelled by the negatively charged soil colloids and thus tend to remain in solution making them vulnerable to leaching. Thus, 300 mm of rainfall will remove almost all chloride ions to below 0.6 m in depth (Rubens, 1978). Sodium is more difficult to remove by this method. This is because as the salt solution percolates through the soil, the sodium, due to its high relative concentration, readily exchanges with other cations such as calcium, magnesium and potassium and becomes bound to the cation exchange sites. To be most effective watering needs to be carried out before growth begins in the spring so that uptake of Na^+ and Cl^- is avoided as much as possible. The main problem with this technique is that on soils prone to waterlogging, watering may exacerbate rather than ameliorate the situation.

Amelioration through soil additives

Gypsum

Gypsum ($CaSO_4$) is a non-acidifying, non-toxic, relatively inexpensive, and readily available substance which has been successfully used to reclaim salt-affected agricultural soils in the United States, USSR, Israel and the Netherlands (Rubens, 1978). It has been suggested that gypsum could also be used to ameliorate the effects of salt in roadside soils (Rubens, 1978; Dirr and Biedermann, 1980; Shaw and Hodson, 1981).

As yet, direct benefits in terms of effects on plants have not often been reported but Dirr and Biederman (1980) found that *Cotoneaster* plants treated with NaCl and $CaSO_4$ showed less than 40% necrosis while plants treated with NaCl alone showed 70–80% necrosis. Gypsum improves conditions for plant growth in salt affected soils principally by reducing soil sodium and chloride levels. The calcium in gypsum displaces sodium from cation exchange sites, because of its high concentration, and once Na^+ is free in solution it combines with sulphate to form Na_2SO_4 which is highly soluble and readily leached from the soil. Tests in Maine, USA, have shown that gypsum was able to reduce sodium in roadside soils by up to 76% in just over a year (Jacobs, 1976). This reduction in soil sodium could lead to a reduction in uptake of Na^+ by plants and a reversal of soil deflocculation caused by Na^+ in clay and silt soils. A reversal of soil deflocculation would result in improved soil capillarity, which allows water to be drawn upwards from the water table during drought (Scotter and Loveday, 1966), and improved soil drainage which increases the rate of leaching of chloride from the soil (Rubens, 1978). Dobson (unpublished) found that gypsum applied to the soil surface of potted hawthorn (*Crataegus monogyna*) at a rate of 2 kg m^{-2} reduced soil chloride concentrations by up to 21%. Similarly Jacobs (1976) showed that applications of gypsum resulted in greater reductions in soil chloride concentrations compared to the non-treated controls.

There is also evidence to suggest that besides reducing soil concentrations of Na^+ and Cl^- gypsum may also enable plants to reduce Na^+ and Cl^- uptake by increasing membrane selectivity (Epstein, 1961; LaHaye and Epstein, 1969). Neirinckx and Stassart (1979) found that in the presence of $CaSO_4$ translocation of Na^+ in the roots of NaCl-treated barley was inhibited and Hansen and Munns (1988) found that for *Leucaena leucocephala* grown in a nutrient solution containing NaCl and $CaSO_4$, uptake of Na^+ decreased as $CaSO_4$ concentration increased.

Gypsum can be applied to the soil surface around existing trees or mixed in with backfill for new plantings. Dirr and Biedermann (1980) found that incorporated gypsum proved to be more effective than surface applications, an observation confirmed by Rubens (1978). At present, with little detailed research available, one cannot improve upon the suggestion that gypsum should be applied at the rates found suitable for agricultural soils, i.e. 0.9–3.3 kg m^{-2} (Rubens, 1978). While treatment is likely to be most effective if application is made prior to the beginning of winter salting operations, application following salting may still be of some value. As gypsum is only about 25% soluble (Rubens, 1978) one application may continue to have beneficial effects for several years.

Fertilisers

Decreased availability of nutrients in the soil and impaired ion selectivity in plant roots leading to altered nutrient balance are partly responsible for the damage caused by salt (see Chapter 3). Attempts to ameliorate salt damage through watering or by the addition of gypsum to the soil have the disadvantage that they are likely to exacerbate these nutritional imbalances by leading to the leaching of beneficial cations such as K^+ and Mg^{2+}, as well as Na^+, from the soil. These treatments should therefore be complemented with the use of fertilisers to restore nutrients such as N, P, K and Mg. Phosphate, nitrate and sulphate are all able to reduce the uptake of chlorides to varying degrees, and phosphates increase the exchangeability of Ca^{2+} for Na^+ in the soil thus improving the effectiveness of gypsum.

Phosphates applied to the foliage of peanut plants (*Arachis hypogaea*) growing in saline soils increased dry weight, leaf area, stomatal frequency, and yield. This was linked to a reversal in the decline of foliar P, K and Ca caused by salinity, and a reduction in the accumulation of Na (Malakondaiah and Rajeswararao, 1979). Similarly, Ravikovitch and Yoles (1971) found that phosphate fertilisation improved growth of millet and clover growing in NaCl treated soil, and allowed the plants to tolerate higher salinities. Flückiger and Braun (1981) treated young potted ash (*Fraxinus excelsior*) with NaCl and a nutrient solution ($Ca(NO_3)_2$: KNO_3: $MgSO_4$: KH_2PO_4; 10:5:2:1) and found that trees treated with NaCl alone had higher water potentials, decreased stomatal conductance and more severe leaf necrosis. Further experiments showed that injury to potted *Viburnum opulus* was decreased when the nutrient solution was applied to the salinized soil. The effect of the nutrient solution was also examined in a field experiment. Young *Pinus nigra* were planted in autumn in the central reservation of a motorway near Basel and were thereby exposed to salt in the soil and salt spray during the following winter. Plants treated once with 2 litres of nutrient solution in the spring showed a lower death rate after one and two years than trees which did not receive this treatment. Mekdaschi *et al.* (1988) fertilised salt-damaged horse chestnut (*Aesculus hippocastanum*) in Stuttgart with NPK fertiliser (ratio not specified) and found that treatment reduced foliar Na^+ and Cl^- concentrations and also reduced visible damage. They suggested that with gypsum and fertiliser treatment severely damaged trees could be brought back to health in 5–10 years.

Amelioration through design and engineering

Some of the potential problems arising out of the use of de-icing salt could be reduced by appropriate action at the planting stage. This would involve balancing the opposing requirements of providing the tree with a supply of water during the summer and protecting it from salt-contaminated water during the winter. To date little effort has been expended in determining how this could be achieved with a minimum of cost. A possible solution might be to plant trees in raised planting beds so that salt water does not collect in the tree's rooting area. However, this should be combined with the retention of a sufficiently large open area of soil around the tree so that moisture from precipitation is available to the tree during the summer.

Hvass (1985, 1986) describes measures for protecting trees during winter that have been tested in Denmark. Guards made of straw and plastic are placed around street trees at the beginning of winter to prevent salt being splashed on to the soil around the tree base and also to prevent salty snow being piled against the tree from snow ploughing operations. These reports contain no detailed information about the effectiveness of this type of protection but it seems that trees thus protected have a greater survival rate.

It has been suggested that leaky drains carrying salty runoff contribute to tree damage, and if this is true then the above measures will be of little value. However, no work has been carried out to assess whether leaking drains contribute significantly to tree damage. Further research by arborists and engineers in each of the areas mentioned above is urgently needed.

Conclusions

There is considerable scope for reducing salt damage to trees. Salt usage could be decreased to 40% of present day levels if salt was more efficiently stored and spread. Further substantial reductions in salt usage could be made if European spreading patterns were adopted (e.g. wet salt technique) and if all the available technology for ice prediction was used. This reduction should be possible without any loss of road safety. At present there are insufficient data to assess whether reductions of salt usage have been achieved since the Audit Commission report was published in 1988.

Even if the recommendations for reducing salt usage are being acted upon, there remains considerable scope for the use of alternative de-icers which are not damaging to the environment. Calcium magnesium acetate is the most promising alternative to salt as it is virtually non-corrosive and on present evidence appears to be non-damaging to trees. Although CMA is about 20 times as expensive as salt it must be borne in mind that the overall cost of salt (taking into account environmental damage) is in the region of 10–15 times the purchase price.

From the literature it appears that salt damage may be best ameliorated by a combination of irrigating the soil with water and addition of gypsum and fertiliser. There are, however, very few detailed studies on the effects of these treatments on roadside trees. There remains, therefore, much research to be carried out to determine when and how treatments should be given.

Avoidance of damage by design and engineering is an area that has received very little attention and requires further research.

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