

Factors Affecting Snow Damage of Trees with Particular Reference to European Conditions

Marja-Leena Nykänen, Heli Peltola, Christopher Quine,
Seppo Kellomäki and Marianne Broadgate

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Within the European Community snow damage affects an estimated 4 million m³ of timber every year, causing significant economic losses to forest owners. In Northern Europe, for example, the occurrence of snow damage has increased over the last few decades mainly due to the increase in total growing stock. The most common form of damage is stem breakage, but trees can also be bent or uprooted. Trees suffering snow damage are also more prone to consequential damage through insect or fungal attacks.

Snow accumulation on trees is strongly dependent upon weather and climatological conditions. Temperature influences the moisture content of snow and therefore the degree to which it can accumulate on branches. Wind can cause snow to be shed, but can also lead to large accumulations of wet snow, rime or freezing rain. Wet snow is most likely in late autumn or early spring. Geographic location and topography influence the occurrence of damaging forms of snow, and coastal locations and moderate to high elevations experience large accumulations. Slope plays a less important role and the evidence on the role of aspect is contradictory. The occurrence of damaging events can vary from every winter to once every 10 years or so depending upon regional climatology. In the future, assuming global warming in northern latitudes, the risk of snow damage could increase, because the relative occurrence of snowfall near temperatures of zero could increase.

The severity of snow damage is related to tree characteristics. Stem taper and crown characteristics are the most important factors controlling the stability of trees. Slightly tapering stems, asymmetric crowns, and rigid horizontal branching are all associated with high risk. However, the evidence on species differences is less clear due to the interaction with location. Management of forests can alter risk through choice of regeneration, tending, thinning and rotation. However, quantification and comparison of the absolute effect of these measures is not yet possible. An integrated risk model is required to allow the various locational and silvicultural factors to be assessed. Plans are presented to construct such a model, and gaps in knowledge are highlighted.

Keywords snow damage, stem breakage, snowfall, stand management, risk assessment

Authors' addresses *Nykänen, Peltola* (corresponding author) and *Kellomäki*, University of Joensuu, Faculty of Forestry, P.O. Box 111, FIN-80101 Joensuu, Finland; *Quine*, Forestry Commission Research Division, Roslin, United Kingdom; *Broadgate*, Macaulay Land Use Research Institute, Aberdeen, United Kingdom **Fax** +358 13 251 4444 **E-mail** heli.peltola@forest.joensuu.fi

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1 Introduction

Snow damage is a significant problem in boreal, maritime temperate and mountain forests. For example, within the European Community snow damage affects an estimated 4 million m³ of timber every year. Snow damage can cause significant economic losses to forest owners through reduction of timber quality and timber volumes in damaged stands (e.g. Juutinen 1953, Suominen 1963, Valinger and Lundqvist 1992a). As the commonest form of damage is stem breakage the loss in value of timber can be particularly severe. A further consequence of snow damage is the increased risk of attack by insects and fungi (e.g. Rottmann 1985a, Valinger and Lundqvist 1992a, 1994). The location of snow damage in forests depends mostly on weather and climatological conditions, but the topography of a site also affects the probability of snow damage occurrence (Persson 1972, Norokorpi 1981, Rottmann 1985a, Solantie 1994). The trees and stands damaged depend upon tree characteristics which are determined by the species and stand management regimes (e.g. Petty and Worrell 1981, Valinger et al. 1993).

This review summarises the literature available on factors affecting snow damage with particular reference to Europe, especially Northern Europe, Central Europe and Britain, proposes ways to reduce the risk of snow damage, and identifies further work required. The literature does not always distinguish between damage caused by accumulation of snow, and that caused by rime (fog droplets freezing on surfaces) or freezing rain (rain or drizzle that freezes on impact); although the mechanical effects may be similar the pattern of loading may differ – in particular these freezing droplets will accumu-

late on the windward side of objects. This review concentrates on damage caused by snow but refers to the other damage types where appropriate.

2 Description of Snow Damage to Trees

Snow damage is caused by large amounts of snow accumulating on tree crowns and stems (e.g. Solantie and Ahti 1980, Solantie 1994). This accumulation exerts additional stresses upon the crown, stem and roots of trees (Persson 1972, Worrell 1979). Failure of a particular component of the tree to resist this additional loading will result in crown or stem breakage, stem bending or uprooting (Williston 1974, Worrell 1979, Petty and Worrell 1981, Pertilä 1987, Slodicák 1995). Once this has occurred there is an increased risk of consequential damage (Valinger and Lundqvist 1992a, 1992b, 1994). Effects on tree form caused by abrasion of ice crystals on foliage are not considered here (Wooldridge et al. 1996).

2.1 Stem and Crown Breakage

Stem breakage is the most common type of snow damage, especially in middle-aged (pole stage) or mature stage stands (Williston 1974, Braastad 1978, Worrell 1979, Petty and Worrell 1981, Pertilä 1987, Slodicák 1995). This type of damage occurs when stem resistance to bending is lower than root anchorage strength (Valinger and Lundqvist 1992a, 1992b, 1994). Resistance to

stem breakage seems to increase as a function of dbh³ (dbh = breast height diameter) (Petty and Worrell 1981, Jones 1983, Petty and Swain 1985, Peltola and Kellomäki 1993). However, it is also affected by modulus of rupture, which varies depending on tree species, wood density and knottiness (i.e. growth rate and spacing) (Lavers 1969). The modulus of elasticity, which also varies between different tree species, affects the ability of a tree to resist stem deflection under snow loading and finally stem breakage (e.g. Petty and Worrell 1981, Peltola et al. 1997a). Breakage can occur at a variety of heights (Ffolliot and Thompson 1976, Worrell 1979) but a position at 25–30 % of tree height as measured from the stem base (Rottmann 1985a) has been suggested as common. Variability in point of breakage has been attributed to species and age. For example, crown breakage is typical in Norway spruce (*Picea abies* L.) (Juutinen 1953, Samuelson 1970, Valinger et al. 1994), but stem breakage can occur in the middle of the crown, beneath the crown, and near the stem base in Scots pine (*Pinus sylvestris*) and birch sp. (*Betula* sp.). In practice, the precise point of breakage will depend also upon stem taper, wood strength, and presence of defects such as knots, whorls and rot. At present there is no clear understanding of the relative effects of these different factors on the mechanism of tree failure.

The subsequent impact of damage depends partly on the position at which breakage occurs. If a stem breaks below the living crown the tree will die (Heikinheimo 1920, Worrell 1979). When fracture occurs within the living crown, it causes a loss of dominance and increment rates subsequently fall (Schöpfer 1964, Armescu 1973, Worrell 1979). Although damaged trees often recover satisfactorily, damage still causes direct timber loss. Stems tend to be crooked, forked and have multiple leaders (e.g. Heikinheimo 1920, Williston 1974, Norokorpi and Kärkkäinen 1985) particularly if the trees have been damaged in more than one event. The duration of recovery is dependent on the height of breakage, age of tree (Juutinen 1953), and tree species (Williston 1974). Stem and crown breakage also increases the susceptibility of trees and stands to fungal and insect attack (Juutinen 1953, Rumukainen 1967, Williston 1974, Megahan and

Steele 1987, Schroeder and Eidmann 1993, Valinger and Lundqvist 1994).

2.2 Stem Bending

Stem bending can be caused by snow loading of tree crowns or lateral movement of the snow pack. Stem bending may be manifested in bending of upper stem or sweep of the lower stem. It has been reported in many coniferous species (Williston 1974, Ffolliot and Thompson 1976, Worrell 1979) and in some deciduous tree species (Samuelson 1970). The stems of small trees may suffer bending without any visible fractures (Solantie 1994), although basal bow of young trees can result (Sugiyama and Saeki 1963, Goebel and Deitschman 1967, Kangur 1973, Gill 1974, Shepard 1975, Worrell 1979, Perttilä 1987). Trees of small diameter are believed to be more prone to bend than to other forms of snow damage (Rottmann 1985a, Megahan and Steele 1987, Sampson and Wurtz 1994).

Snow induced bending in trees may persist for several years or only a few months (Schmidt and Schmidt 1979); in extreme cases the tree may never recover. The degree to which a tree recovers depends on the angle of bending (Curtis 1936, Williston 1974). Some pines which have been bent by as much as 40° have been found to recover satisfactorily, whereas trees bent beyond 60° never recover (Williston 1974). Repetitive loading may prevent recovery and lead to breakage (Heikinheimo 1920, Curtis 1936). Bending reduces height growth (Megahan and Steele 1987), but it may also cause compression failures in timber on the concave (Rendle et al. 1941, Mergen and Winner 1952, Williston 1974, Worrell 1979) or downhill side of the stem (Megahan and Steele 1987). Heikinheimo (1920) has suggested that in northern Finland, wood was weaker on the southern sides of stems where snowloads tend to accumulate.

2.3 Uprooting

Snow loading can also cause uprooting of trees when the ability of stems to resist bending and breakage is greater than the root anchorage

Table 1. Species most commonly associated with consequential insect attack after snow damage.

Insect	Tree species	References
<i>Tomicus</i> sp. (pine shoot beetles)	<i>Pinus sylvestris</i> (Scots pine)	Juutinen 1953, Persson 1972 Rottmann 1985a
<i>Pissodes</i> sp. (pine weevils)	<i>Pinus sylvestris</i>	Rottmann 1985a
<i>Rhizophagidae</i> sp. (Rhizophagidae-beetles)	<i>Pinus sylvestris</i>	Rottmann 1985a
<i>Pityogenes chalcographus</i> (Pityogenes-beetle)	<i>Picea abies</i> (Norway spruce)	Persson 1972, Rottmann 1985a
<i>Ips typographus</i> (spruce bark beetle)	<i>Picea abies</i>	Persson 1972, Rottmann 1985a
<i>Siricidae</i> sp. (wood wasps)	<i>Pinus sylvestris</i> & <i>Picea abies</i>	Rottmann 1985a
<i>Trypodendron lineatum</i> (spruce ambrosia)	<i>Pinus sylvestris</i> & <i>Picea abies</i>	Rottmann 1985a
<i>Cerambycidae</i> sp. (longhorn beetles)	<i>Pinus sylvestris</i> & <i>Picea abies</i>	Rottmann 1985a

strength (Valinger and Lundqvist 1992a). Uprooting does not occur as often as stem breakage (e.g. Kangur 1973, Worrell 1979). This may be due to the fact that in some countries, for example in Northern Europe, forest soils are usually frozen at the time of the heaviest snow loading (Peltola et al. 1997b). However, resistance to uprooting has been found to be a function of height \times dbh², rather than dbh³, which means that uprooting is less strongly dependent on dbh than breakage (Gardiner et al. 1997). Some species, such as young Scots pines, seem to be more susceptible to uprooting than to stem breakage (Solantie 1994). This may be due to an imbalance in the biomass allocation between roots and above ground part of a tree. Uprooting may result in complete upheaval of the root system. Roots may also be loosened leading to toppling and socketing of the tree. Root development and soil conditions influence this type of failure and impediments to symmetric root development through ground slope, the presence of rocks, waterlogging or plough furrows will predispose trees to overturning (Sanzen-Baker and Nimmo 1941, Worrell 1979, Solantie 1994).

2.4 Consequential Damage

Following snow damage, trees are often susceptible to several kinds of consequential damage (Schroeder and Eidmann 1993). Both insect and fungal attacks can occur and can lead to difficulties in regeneration (Rottmann 1985a). The insects which most affect trees after snow damage are presented in Table 1, for species for which information was available, i.e. Scots pine and Norway spruce. Trees which have lost more than half of their crowns are likely to be damaged by insect attack (Juutinen 1953). This may cause reduced growth rates and a reduction in timber quality, and the insects can also spread to undamaged trees (Juutinen 1953, Persson 1972, Rottmann 1985a). The combined treatments of thinning and fertilization may also increase the risk of snow damage and windthrow and consequential insect damage to the entire stand (Valinger and Lundqvist 1992b). Therefore, it is important to take care of forest hygiene after snow damage (Juutinen 1953) and remove damaged trees (Samuelson 1970, Valinger and Lundqvist 1992b, Valinger et al. 1994).

According to Juutinen (1953), fungal damage after snow damage is more common for Norway spruce and birch sp. than for Scots pine. The effects of fungal attack are dependent on the tree age, the diameter of the breakage and the height of the crown remaining after snow damage. The larger the extent of living crown which remains, the less probable it is that rot will develop (Rottmann 1985a). In Germany, for example, some of the typical fungal types which infect trees as a consequence of snow damage are bleeding sterium (*Stereum sanguinolentum*) and root rot (*Fomes* sp.). Trees infected by fungal diseases after frequent thinning may be more liable to further snow and wind induced damage (Samuelson 1970, Perttilä 1987). Consequential damage causes major economical losses due to timber degrade and loss of volume of quality timber. In addition, the harvesting costs in damaged forests are increased and the establishment of regeneration may also become difficult (Juutinen 1953, Persson 1972, Valinger and Lundqvist 1992b, Valinger and Lundqvist 1994, Rottman 1985a).

3 Effects of Weather and Climatological Factors

3.1 Interaction of Temperature and Windspeed with Quantity and Type of Snow

Accumulation of snow on trees sufficient to cause snow damage depends upon the quantity of snow and the type of snow. These are determined by weather conditions, primarily the windspeed and the temperature (see Fig. 1), which are in turn influenced by time of year, location and topography (Heikinheimo 1920, Gill 1974, Solantie and Ahti 1980, Rottmann 1985a, Solantie 1994). Excessive loading of snow over a winter in continental conditions can cause damage (Heikinheimo 1920, Norokorpi 1981, Sampson and Wurtz 1994).

The process of snow interception by trees is complex and involves components of through-fall, adhesion, cohesion, wind removal, sliding, melting and vapour transport (Keller 1979). The

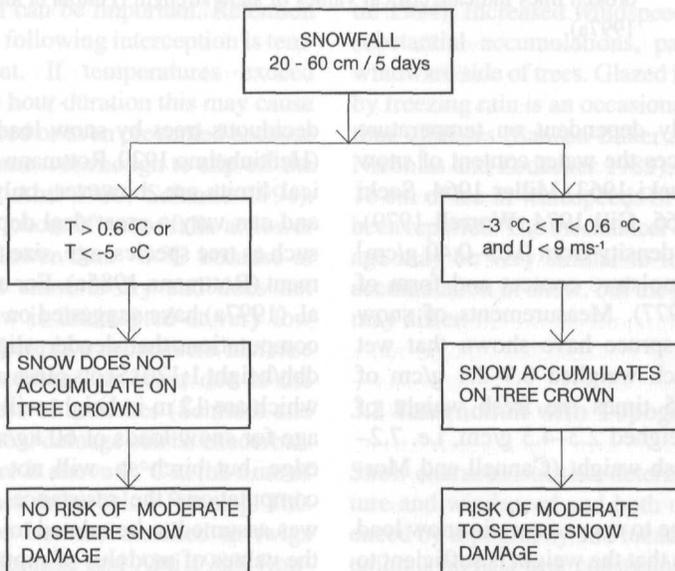


Fig. 1. Effects of temperature (T) and windspeed (U) on snow accumulation on tree crowns and on the risk of moderate to severe snow damage in Northern Europe. The limit is set for low or moderate at about 40 mm and for severe at over 60 mm of precipitation (Solantie 1994).

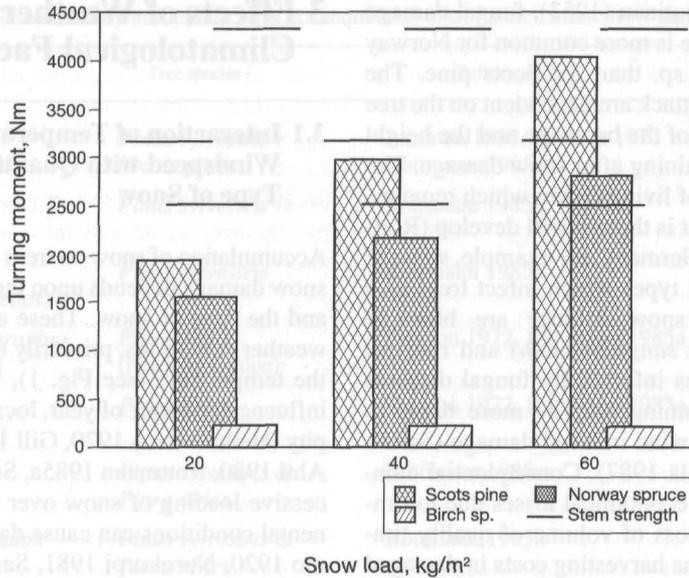


Fig. 2. Snow loading of 60 kg/m² may cause stem breakage in Scots pine and Norway spruce along the stand edge, but is not sufficient to cause breakage in birch sp. (for trees 12 m tall with taper 1:120). Columns indicate combined loading of snow and wind, where windspeed is taken as a constant of 8 m/s above the canopy top. The broken lines indicate critical values of stem strength (Peltola et al. 1997a).

process is strongly dependent on temperature because it influences the water content of snow (Sugiyama and Saeki 1963, Miller 1964, Saeki and Sugiyama 1965, Gill 1974, Worrell 1979). Snow can vary in density from 0.05–0.40 g/cm³ depending upon moisture content and form of snow (Jackson 1977). Measurements of snow loading of Sitka spruce have shown that wet snow 4–8 cm thick weighed 0.9–2.1 g/cm³ of shoot, i.e. 3.1–4.5 times the fresh weight of branches; rime weighed 2.3–4.3 g/cm³, i.e. 7.2–11.7 times the fresh weight (Cannell and Morgan 1989).

For snow damage to occur a certain snow load must develop such that the weight is sufficient to break components of individual trees. Failure may occur when the accumulation reaches a critical value during a single snow event or after prolonged loading. Coniferous trees have been found to suffer damage by snow loads of approximately 50 kg/m² (i.e. snowfall 50 cm), and

deciduous trees by snow loads under 25 kg/m² (Heikinheimo 1920, Rottmann 1985a). These critical limits are, however, only rough estimates and can vary a great deal depending on factors such as tree species, age, size and stand management (Rottmann 1985a). For example, Peltola et al. (1997a) have suggested on the basis of model computations that slender, slightly tapering (e.g. dbh/height 1:120) Scots pines and Norway spruce which are 12 m in height will suffer snow damage for snow loads of 60 kg/m² along the stand edge, but birch sp. will not (Fig. 2). In these computations the resistance to stem breakage was assumed to be related to dbh³, and 70 % of the values of modulus of rupture obtained from static tests of clear wood were used as the critical values under short term loading (Lavers 1969, Petty and Worrell 1981); thus, values of 32, 25 and 44 MPa for Scots pine, Norway spruce and birch sp. were used as estimates for the strength of green wood (Peltola et al. 1997a).

The most favourable conditions for snow accumulation are light winds, falling air temperatures and no sunshine. Cohesion and adhesion of snow is greatest at temperatures just below freezing. Large snow loads tend to accumulate rapidly and evenly on crowns at temperatures in the range +0.6 to -3 °C, when the size and form of snow flakes are most suitable for accumulation (Saeki and Sugiyama 1965, Worrell 1979, Solantie 1994). It has been suggested that the right conditions for damaging snowfalls can occur even with temperature ranges from +3 to -5 °C (Saeki and Sugiyama 1965, Worrell 1979). The narrow temperature ranges for optimal accumulation are often manifested as clear bands or zones of localised damage controlled by altitude and distance from the coast (Suominen 1963, Worrell 1979).

Snow accumulation occurs by the formation of a platform on tree needles during initial accumulation, upon which subsequent flakes can accumulate producing a loading effect (Heikinheimo 1920, Kangas 1959, Suominen 1963, Hoover and Leaf 1965, Satterland and Haupt 1967, Worrell 1979, Solantie 1994). Conditions after the initial snowfall can be important. Retention of snow on crowns following interception is temperature dependent. If temperatures exceed +0.6 °C for a three hour duration this may cause damage to be reduced or even prevented because the snow will become wet enough to slip off the tree (Solantie and Ahti 1980, Solantie 1994). Shedding can also occur if snow falls at lower temperatures e.g. lower than -5 °C because at these temperatures snow is dry and does not adhere. When snow is intercepted at very low temperatures and there is a subsequent increase in temperature, shedding can occur due to the reduction in stiffness of branches (Schmidt and Pomeroy 1990). Snow damage can be exacerbated if the temperature is above 0 °C at the time of precipitation and then drops below freezing. This causes the snow to become attached to twigs more effectively (Solantie and Ahti 1980, Rottmann 1985a, Solantie 1994). Strong winds may break trees which are already heavily loaded by snow (Valinger and Lundqvist 1992b).

However, in normal conditions in Northern and continental Europe low windspeed is a further meteorological condition that favours large

snow accumulations, particularly when the snow is wet (Sugiyama and Saeki 1963, Saeki and Sugiyama 1965, Hoover and Leaf 1965, Kangur 1973, Gill 1974, Worrell 1979). If windspeeds exceed 9 m s⁻¹, the unattached snow can be dislodged (Solantie 1994). On the other hand, in maritime regions, in blizzard conditions of strong winds and wet snow it is still possible for severe snow loading to occur. Windspeeds of around 25 m s⁻¹ were recorded during a snow damage event in Britain responsible for 80 000 m³ of timber being damaged in a localised area (Wright and Quine 1993). Although this combination of strong winds and snow is unusual in Britain it is not unique (e.g. Watson 1936, Frank 1948) and occurs in other parts of the world (Guild 1986). Unfortunately, there are few studies on the combined effects of wind and snow loading and not much statistical information is available (Rottmann 1985a, Wright and Quine 1993).

Rain and fog droplets which are intercepted by trees at subzero temperatures may also accumulate as ice or rime, increasing the crown loading on the tree by up to 50–60 % (Hall 1967, Solantie and Ahti 1980, Petty and Worrell 1981, Solantie 1994). Increased windspeeds will encourage substantial accumulations, particularly on the windward side of trees. Glazed ice damage caused by freezing rain is an occasional feature of maritime climates (Sanzen-Baker and Nimmo 1941, Nicholas and Zedacker 1989); accumulations of 10 cm of ice in windspeeds of 18–26 m s⁻¹ have been reported. The mechanical details of the damage may be very similar to that caused by the accumulation of snow, but the pattern of damage may differ.

3.2 Interaction with Topographic Factors

Snow characteristics are determined by temperature and windspeed and both of these are influenced by topography and location. Thus precipitation is highest near coasts and on high ground, windspeeds increase with elevation and temperature decreases with elevation. These influences are reflected in observations of damage.

Location. Snow loads usually form early in the winter in Northern Europe, especially in coastal locations. Proximity to the sea enhances the for-

mation of snow, ice and rime, because moist air is blown inland by prevailing westerly, south-westerly and southeasterly winds (Heikinheimo 1920, Norokorpi 1981, 1994, Norokorpi and Kärkkäinen 1985). The duration and quantity of wet snow precipitation on trees is greater near the sea than inland (e.g. Heikinheimo 1920, Norokorpi 1994). Thus, the highest percentage of heavily damaged stands have been found closest to the coast (Suominen 1963, Valinger and Lundqvist 1992a). In addition, the amount of orographic precipitation, which occurs when topography forces moist air to rise, further increases the risk of snow loading as the wind blows on-shore (Heikinheimo 1920, Solantie and Ahti 1980, Norokorpi 1981, Rottmann 1985a, Norokorpi 1994, Solantie 1994). Similar regional patterns are found elsewhere; for example, the North Yorks Moors, an area of relatively high relief close to the North Sea coast of Britain, has been repeatedly damaged by snow events (Wright and Quine 1993).

Slope and aspect. It would appear that the gradient of the slope has only a minor influence on snow damage. Damage has been reported to be slightly more common on steep slopes (Rottmann 1985a), but it is unclear whether this is due to greater accumulations in calm conditions or to development of asymmetric crowns on such sites (Curtis 1936). Slopes which have been found to be more prone to damage are those with an eastern aspect for southern Finland (Suominen 1963, Solantie and Ahti 1980, Solantie 1994) and with southern and southwestern aspects in northern Finland. In northern Sweden snow damage has tended to occur on south-eastern slopes (Valinger and Lundqvist 1992a) even though, snow loads remain longer on trees with north facing slopes (Heikinheimo 1920). According to Rottmann (1985a, 1985b), snow damage in Central Europe occurs on all slopes, but slopes with northern, northeastern, eastern (and occasionally even southeastern) aspects are most liable to snow damage. Stands most liable to snow damage are often situated on windward slopes (Heikinheimo 1920, Solantie and Ahti 1980). However, Cremer et al. (1983) note that snow damage is often observed to be worse on sheltered sites and on lee slopes than on exposed sites (see also Cremer 1983). The apparently contradictory nature of

these results reflect the variety of synoptic conditions in which snow damage can occur in different regions and continents. In a glazed frost storm in Britain the damage was recorded as most severe on windward slopes (Sanzen-Baker and Nimmo 1941).

Altitude. The amount of snowfall, and therefore damage, are related to altitude, with higher altitude sites generally being at greater risk (Heikinheimo 1920, Persson 1972, Norokorpi and Kärkkäinen 1985, Megahan and Steele 1987, Dittrich 1989, Valinger and Lundqvist 1992a, 1992b, 1994). In Northern Europe, a limit of 100 m has been identified as the height above which damage occurrence increases (Suominen 1963, Valinger and Lundqvist 1992a, 1994) and forested land at altitudes greater than 150–200 m above sea level seem to be most susceptible to snow damage. This is because both the amount of wet snow deposited on tree crowns (Suominen 1963, Perttilä 1987, Valinger and Lundqvist 1992a, 1994) and the duration of snow loading on trees increases at high altitude (Heikinheimo 1920, Mikola 1938, Solantie 1974, Norokorpi 1981). In contrast altitudes of 500–900m are associated with highest incidence of snow damage in Central Europe; damage can occur at any altitude but is unlikely to occur above 1000 m (Rottmann 1985a). These differences between regions probably reflect the variation in elevation where there is high incidence of heavy, wet snowfall (Parez 1972, Rottmann 1985a, Dittrich 1989, Slodicák 1995) and where there is forest adapted to snow accumulation (Mikola 1938, Rottmann 1985a).

3.3 Frequency of Occurrence

Season of damage will depend upon the occurrence of the favoured conditions, and this in turn will depend upon geographic location and climatology. In Northern Europe damage is most likely to occur in late autumn and early spring when the probability of wet snowfall is highest (e.g. Heikinheimo 1920, Norokorpi 1981, 1994). However, in mountain forests of Central Europe damage may occur throughout most of the year, with the exception of the summer months, June, July and August (Rottmann 1985a).

In some areas snow damage may occur almost every year (Heikinheimo 1920), but in others the frequency varies a lot (Rottmann 1985a, Solantie 1994). On the whole, for example in Northern Europe, the occurrence of snow damage has increased over the last few decades mainly due to the increase in total growing stock (Valinger and Lundqvist 1994). Unfortunately, only few snow damage statistics are available (Rottmann 1985a, Solantie 1994). Frequency of damage in Finland has been calculated on the assumption that for low or moderate snow damage, the water equivalent of the snow cover should increase by 40 mm or more over a period of five days (Solantie 1994). Recently, the limit of low and moderate damage has been exceeded on average every 5 years in the south and every 3 years in the north-east. In other parts of Finland, excluding some regions which are at higher elevation, this limit is exceeded every 8 to 17 years (Solantie 1994). In some areas of Germany snow damage has been found to occur every 3.5 to 7 years (Rottmann 1985a). Schroeder and Eidmann (1993) identify 10 winters with severe damage in the last 30 years in Sweden, with annual losses due to snow breakage varying from 100 000 m³ to 1 million m³ per winter. In some years only high elevation sites have been affected, i.e. greater than 400 m. In maritime sites damage may occur infrequently – in Britain the conditions necessary to cause notable damage occur somewhere perhaps once every 10 years, and are far rarer than damage events caused by wind alone (Quine 1995).

The variability in snow type and complex influence of location, topography, windspeed and temperature make it difficult to assess the value of results transferred from one region to another. In some areas, where large snow accumulations are a common feature of the climate, snow damage may conform to a clear geographic pattern. However, in other areas with wide variation in snow accumulation from year to year it may require a considerable period of study to identify patterns of typical damage; the damage in a single event may reflect the particular synoptic conditions lasting perhaps a few hours, and not the climatology of snow.

4 Tree and Stand Characteristics

4.1 Tree Characteristics

Taper and crown characteristics are the main factors which control the resistance of trees to snow and the combined effect of snow and wind (e.g. Persson 1972, Petty and Worrell 1981, Rottmann 1985a, Valinger et al. 1993). Tree species and stand characteristics, particularly stand density, affect the development of these tree characteristics and therefore the susceptibility of trees to snow damage.

Crown type. On the whole, crown size and form are very important (Rottmann 1985a, 1985b, Valinger et al. 1993), because of the larger lever arm (i.e. distance between the centre of gravity of the tree and the ground) (Fig. 3). Trees with asymmetrical crowns are highly susceptible to snow damage (Heikinheimo 1920, Curtis 1936, Mikola 1938, Sanzen-Baker and Nimmo 1941, Haring and Iugu 1970, Persson 1972, Kangur 1973, Williston 1974, Braastad 1978, Worrell 1979, Perttilä 1987). This is, because the stems are subject to bending stresses due to the imbalance in snow loading (Worrell 1979). The narrow crown form has proven to be more resistant to snow damage than other crown forms, because with a smaller horizontal projection area of the tree crown, it has a greatly reduced surface for snow accumulation (Mikola 1938, Persson 1972). Such crown forms occur in natural stands of Norway spruces in high risk areas. In general, coniferous trees with downward hanging branches and narrow crowns (e.g. Norway spruce provenances, *Picea mariana*, *Picea omorica*) seem to be much less susceptible to snow damage (Gill 1974, Rottmann 1985a) than those with rigid horizontal branches and broad crowns (e.g. Scots pine) due to the efficiency of snow shedding (Wakabayashi 1979). Increasing crown depth lowers the centre of gravity of the snow loading making trees more resistant to stem breakage (Heikinheimo 1920, Merkel 1975, Kramer 1975, Rottmann 1985a).

Stem taper. In addition to crown characteristics, stem taper is also an important factor with respect to snow damage of trees. Trees with only slightly tapering stems are most susceptible to

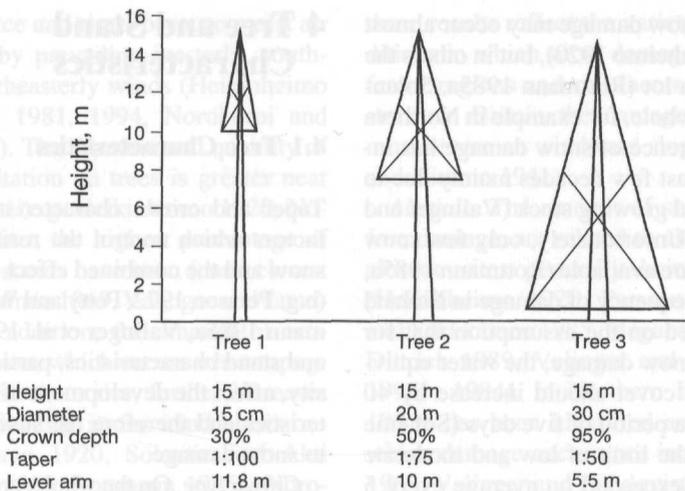


Fig. 3. The risk of snow damage is affected by crown depth, stem taper and height (lever arm) of the gravity centre. The risk of example trees for stem breakage decreases from left to right (adapted from Rottmann 1985a).

breakage caused by snow loading (Mindler 1967, Furuno and Watanabe 1970, Cool and Goebel 1971, Perez 1972, Kangur 1973, Lear and Saucier 1973, Gill 1974, Kramer 1975, Merkel 1975, Abetz and Prange 1976, Ffolliot and Thompson 1976, Braastad 1978, Worrell 1979, Petty and Worrell 1981, Rottmann 1985a, Matthews 1989). Various authors have identified trees which have a taper of less than 1:90 or 1:100 as particularly susceptible (Mindler 1967, Braastad 1978, Worrell 1979, Petty and Worrell 1981, Peltola et al. 1997a). A critical ratio, such as 1:90 is exceeded at different ages, depending on tree species and plant spacing; breast height diameter to tree height-ratio of trees increases with increasing age, and thus the probability of snow breakage decreases in older trees. On the whole, trees with straight, highly tapering stems and tall, live crowns are more resistant to stem breakage than leaning or crooked trees and those with short crowns (Petty and Worrell 1981, Matthews 1989).

4.2 Tree Species

Tree species has a large influence on crown characteristics and stem strength (wood strength), not-

ed above as being important components of tree stability when loaded with snow. In Europe, coniferous trees are generally taken as more susceptible to snow damage than deciduous tree species (e.g. Heikinheimo 1920, Suominen 1963, Samuelsson 1970, Rottmann 1985a). For example, in Northern Europe, it has been found that forests dominated by conifers tend to be more heavily damaged by snow than those dominated by birch sp. (Suominen 1963, Norokorpi 1981, Norokorpi and Kärkkäinen 1985). However, in certain circumstances birch sp. has also been seriously damaged (Kangas 1959, Suominen 1963).

Norway spruce is generally considered to be more resistant to damage than Scots pine (e.g. Heikinheimo 1920, Norokorpi 1981, Perttilä 1987, Valinger and Lundqvist 1992a), even though it provides a greater surface area for snow, glaze and rime accumulation. This apparent resistance may be due to the fact that the weight of snow is more evenly distributed so that the tree's centre of gravity is much lower (Fig. 4). Furthermore, the crown of Norway spruce tends to be more symmetrical and extended than in Scots pine. In high mountain areas such as those in Central Europe, the stem form of Norway spruce

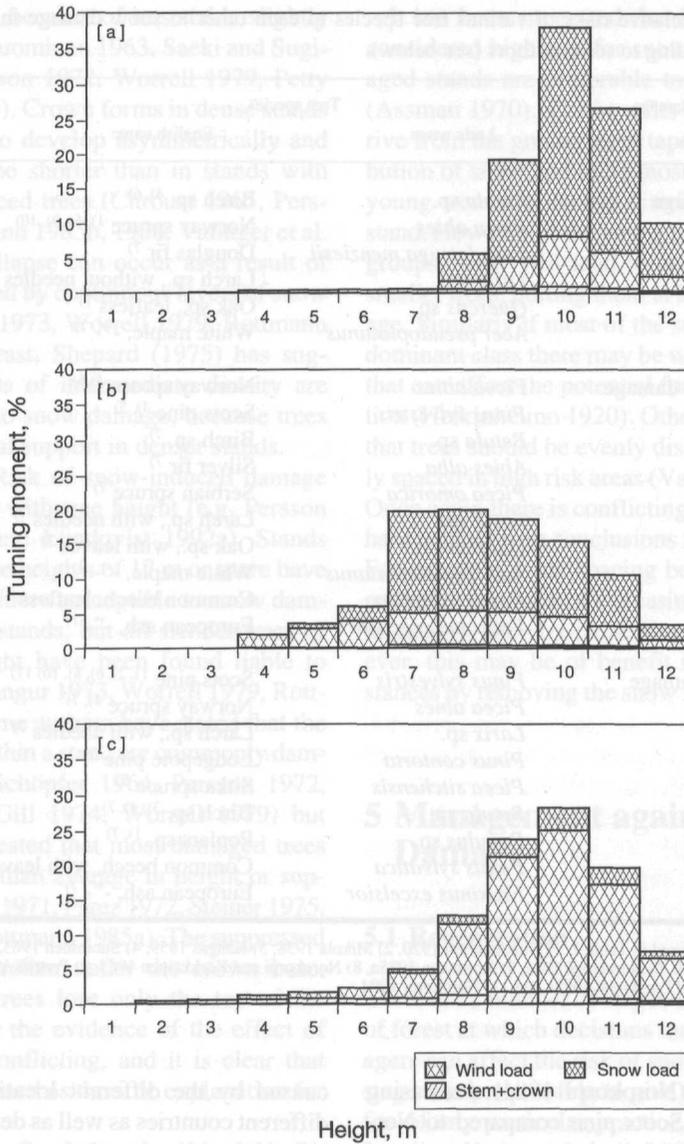


Fig. 4. Examples of the distribution of wind and snow loading with respect to stem and crown weight for Scots pine (above), Norway spruce (in middle) and birch sp. (bottom) for heights of 12 m and tapers of 1:120. Windspeed is 8 m/s at canopy top (Peltola et al. 1997a).

is also abnormally tapered and the crown is narrow (Rottmann 1985a). For Scots pine, the snow loading may be concentrated some distance from the stem's longitudinal axis, thus decreasing the stability of the stem (Heikinheimo 1920, Kangas

1959, Perttilä 1987). The differences in stability may also be due to differences in branch capacity to carry snow and branching habit between species. In the high altitudes of northern Finland, Scots pine suffers from snow damage al-

Table 2. Relative risks of various tree species to each other to snow damage in Europe according to some authors (see below).

Severity of damage	Tree species	
	Latin name	English name
Low damage	<i>Betula</i> sp.	Birch sp. ^{4), 6)}
	<i>Picea abies</i>	Norway spruce ^{1), 6), 9), 10)}
	<i>Pseudotsuga menziesii</i>	Douglas fir ⁷⁾
	<i>Larix</i> sp.	Larch sp., without needles ^{7), 5)}
	<i>Quercus</i> sp.	Oak sp., leafless ⁷⁾
	<i>Acer pseudoplatanus</i>	White maple, -" ⁷⁾
Moderate damage	<i>Picea abies</i>	Norway spruce ^{4), 5)}
	<i>Pinus sylvestris</i>	Scots pine ^{4), 5)}
	<i>Betula</i> sp.	Birch sp. ⁷⁾
	<i>Abies alba</i>	Silver fir ⁷⁾
	<i>Picea omorica</i>	Serbian spruce ⁷⁾
	<i>Larix</i> sp.	Larch sp., with needles ⁷⁾
	<i>Quercus</i> sp.	Oak sp., with leaves ⁷⁾
	<i>Acer pseudoplatanus</i>	White maple, -" ⁷⁾
	<i>Fagus sylvatica</i>	Common beech, leafless ⁷⁾
<i>Fraxinus excelsior</i>	European ash, -" ⁷⁾	
Severe damage	<i>Pinus sylvestris</i>	Scots pine ^{1), 2), 6), 8), 10) 11)}
	<i>Picea abies</i>	Norway spruce ^{4), 7)}
	<i>Larix</i> sp.	Larch sp., with needles ⁷⁾
	<i>Pinus contorta</i>	Lodgepole pine ⁵⁾
	<i>Picea sitchensis</i>	Sitka spruce ⁵⁾
	<i>Betula</i> sp.	Birch sp. ^{3), 4), 7)}
	<i>Populus</i> sp.	Poplars sp. ^{1), 7)}
	<i>Fagus sylvatica</i>	Common beech, with leaves ⁷⁾
	<i>Fraxinus excelsior</i>	European ash, -" ⁷⁾

References used in Table 2: 1) Heikinheimo 1920, 2) Mikola 1938, 3) Kangas 1959, 4) Suominen 1963, 5) Worrell 1979, 6) Norokorpi 1981, 7) Rottmann 1985a, 8) Norokorpi and Kärkkäinen 1985, 9) Perttilä 1987, 10) Valinger and Lundqvist 1992a and 11) Norokorpi 1994

most every year (Norokorpi 1981) decreasing the proportion of Scots pine compared to Norway spruce up to a risk limit for snow damage of 260–330 m. Therefore, Norway spruce-dominated, uneven-aged stands form the upper forest limit in the high slopes of northern Finland (Heikinheimo 1920, Norokorpi 1981, 1994, Norokorpi and Kärkkäinen 1985).

Although there are some clear differences in mechanical terms, there is also confusion between stability of species, which can be seen in Table 2, where susceptibility of various tree species is presented. Thus, Norway spruce appears in each damage category. Lack of clarity in classification of risk of various tree species may be

caused by the different location of species in different countries as well as definitions and classifications of various references. An inability to control for multiple factors makes simple conclusions e.g. ranking of species drawn from the occurrence of damage difficult and potentially misleading (Wright and Quine 1993).

4.3 Stand Characteristics

Stand density. In young dense stands, a heavy drifting snowfall can cause widespread damage as snow settles and consolidates, causing dense stands to suffer heavier damage than sparsely

populated stands, because of less stable slightly tapering stems (Suominen 1963, Saeki and Sugiyama 1965, Persson 1972, Worrell 1979, Petty and Worrell 1981). Crown forms in dense stands are more likely to develop asymmetrically and crowns tend to be shorter than in stands with more widely spaced trees (Chroust 1965, Persson 1972, Rottmann 1985b, 1986, Valinger et al. 1993). Group collapse can occur as a result of the pressure caused by continuous layers of snow loading (Kangur 1973, Worrell 1979, Rottmann 1985a). By contrast, Shepard (1975) has suggested that stands of intermediate density are most vulnerable to snow damage, because trees can receive mutual support in denser stands.

Stand height. Risk of snow-induced damage usually increases with tree height (e.g. Persson 1975, Valinger and Lundqvist 1992a). Stands with dominant tree heights of 17 m or more have been found to be more susceptible to snow damage than shorter stands, but all slender trees of 10–20 m in height have been found liable to snow damage (Kangur 1973, Worrell 1979, Rottmann 1985a). Some authors have stated that the dominant trees within a stand are commonly damaged by snow (Schöpfer 1964, Persson 1972, Armescu 1973, Gill 1974, Worrell 1979) but others have suggested that most damaged trees have been lower than average in height or suppressed (Schubert 1971, Perez 1972, Steiner 1975, Braastad 1978, Rottmann 1985a). The suppressed trees are often broken under the crown base, while dominant trees lose only the top of the crown. Therefore the evidence of the effect of stand height is conflicting, and it is clear that height cannot be used as the sole explanation for damage.

Stand uniformity. Snow damage, in both Northern and Central Europe, can occur in mature stage stands (Suominen 1963, Valinger and Lundqvist 1992a, 1992b, Rottmann 1985b). At this age, shade trees such as Norway spruce, are most commonly damaged, especially during the stage of height growth culmination (Rottmann 1985a, 1985b, Slodicák 1995). One reason may be the fact that these age classes have often been intensively thinned (Suominen 1963). Scots pine, like other light-demanding tree species, are most vulnerable to snow damage during the thicket stage (Rottmann 1985a).

It has been suggested that in areas which are considered high risk for snow damage, uneven-aged stands are preferable to even-aged stands (Assman 1970). The benefits are claimed to derive from the greater stem taper, and even distribution of snow and to be most marked when the young trees are evenly distributed through the stand. However, if the young trees are growing in groups, snow will tend to accumulate on these smaller trees, putting them at higher risk of damage. Similarly if most of the stems belong to the dominant class there may be widespread damage that can affect the potential for natural regeneration (Heikinheimo 1920). Others have suggested that trees should be evenly distributed and widely spaced in high risk areas (Valinger et al. 1993). Once again there is conflicting evidence and it is hard to draw firm conclusions from the evidence. For example, wide spacing between trees has a potential drawback of increasing windspeed within canopy, thereby increasing wind load. However, this may be of benefit in certain circumstances by removing the snow from the branches.

5 Management against Snow Damage

5.1 Regeneration

There are a number of stages in the management of forest at which decisions made by forest managers can affect the risk of snow damage. At this stage it is not possible to give the absolute benefits of any particular practice, but rather weigh up the relative merits of different strategies (Quine et al. 1995).

Choice of regeneration method. It has been postulated that natural regeneration minimizes snow damage (Persson 1975). However, others have noted that plantations have suffered only minor damage in the same areas where natural stands have been damaged severely, because trees in the plantations are uniformly spaced and have balanced crowns (Williston 1974). If artificial regeneration is used, tree spacing and the method used to sow seeds are important factors. In seedling stands that have been regenerated by

sowing, substantial damage has occurred. Broadcast sowing, in particular, appears to increase risk as compared to drill sowing (Kunze 1897, see Persson 1972). Whereas Pertilä (1987) has recommended sowing rather than planting, Persson (1972, 1975) has claimed that the difference is minimal in terms of snow damage risk. However, if planting is used, then bare-root plants seem to produce higher risk stands than ball-seedlings. Thus, in order to prevent snow damage it is recommended that small ball-seedlings are used, because their ability to anchor is much better (Persson 1975). Damage will be most apparent where a uniform spread and depth of root system is not achieved. This may result from rough handling, inappropriate containers and restriction of roots due to plough furrows or other obstacles, e.g. old stumps (Quine et al. 1991, Quine et al. 1995).

Choice of species and provenance. On the whole, in planted stands it is very important to use local or similarly resistant seed sources. If seeds are transported from more southern, warmer, more maritime or lower elevation regions, they tend to be more susceptible to snow damage (e.g. Kalela 1937, Suominen 1963, Persson 1972, Schneckengerber et al. 1985, Megahan and Steele 1987). This is most often due to the crown form being unadapted to the snow loading. For example, in Britain heavily crowned coastal provenances of lodgepole pine have suffered more snow damage than lightly crowned trees from inland sources (Worrell 1979). The coastal provenance also displayed basal sweep which further predisposed it to damage as the stem weight was displaced laterally from the root system (Lines 1980, Lines 1996).

Although it is best to use resistant tree species in high risk areas (Sanzen-Baker and Nimmo 1941, Williston 1974, Rottmann 1985b) it may not be easy to identify these without trials. A heavy dependence placed on observational evidence may be misleading. In Central European conditions Rottmann (1985a) has suggested substituting Norway spruce and Scots pine with Douglas fir or deciduous tree species, which have been identified as more resistant to snow damage. However, it is far from clear whether such species would survive and grow on the sites of highest risk currently occupied by Scots pine

and Norway spruce. Another possible way to increase resistance against snow loading is to grow trees in mixed stands or to follow natural succession (Rottmann 1985b). Each of these decisions is potentially costly.

Choice of initial spacing. Increased planting density seems to increase the occurrence of snow damage, because of the consequent decrease in tree taper (Andersson 1967, Persson 1972, 1975, Cremer et al. 1983, Slodicák 1995). Johann (1981) has suggested that most snow damage occurs for high stocking densities (e.g. 6900 seedlings/ha). Planting densities of 1700 to 3000 seedlings/ha have been recommended as being more resistant to snow damage (Persson 1972) and widely spaced planting strategies as most appropriate at high altitudes in high risk areas (Rottmann 1985a, 1985b). It has been claimed that the benefits of such strategies can outweigh the disadvantages of the economically poor height diameter ratio that results (Johann 1981).

5.2 Tending of Seedling Stand

Wide spacing increases protection and minimizes snow damage by stimulating diameter growth. The low rate of cleaning (self-thinning) of seedling stands can increase the risk for snow damage (Andersson 1967, Samuelson 1970, Persson 1972). Unthinned, young and dense stands with closed canopies are most liable to snow damage because these trees tend to be slender and unstable, and so it is important to thin the groups of plants. Thus, early respacing is very important for dense seedling stands (Slodicák 1995) to allow good root and stem development, especially in stands which have been regenerated by sowing (Persson 1975). It has been suggested that stands should be cleaned (Johann 1981) to a stocking density of about 2000 seedlings/ha when the mean height is between 2 and 3 m depending on site class and tree species (Samuelsson 1970).

Stems and roots will have stabilized before stems reach the critical height for snow loading if seedling stands are tended or thinned efficiently and early enough (Samuelson 1970, Persson 1972, Valinger and Lundqvist 1992a). Snow damage of seedlings can also be reduced by leaving some larger trees to provide shelter from snow

loading. According to Johann (1981), snow damage is more likely to occur within the 3 to 5 year period after cleaning of the seedling stand.

5.3 Thinning

Thinning age. Trees in unthinned stands are usually susceptible to snow damage (Schubert 1971, Persson 1972, Rottmann 1985a). To reduce snow damage by improving taper development, first thinning should be done when the mean height is 10 m or less. Tree spacing to promote suitable taper can also be achieved via heavy thinning after canopy closure (Cremer et al. 1983, Slodičák 1995). If cleaning of the stand has been done early enough or seedlings have been planted with wide enough spacing, the first thinning can be left until a mean height of 15 m is reached (Persson 1972, Johann 1981). If thinning is delayed until tree height reaches 20 m, the risk of snow damage will increase (Samuelsson 1970, Persson 1972, Rottmann 1985a).

Thinning pattern. It has been suggested that low thinning (i.e. selective thinning from below) reduces the risk of snow damage, because slender and smaller trees are removed (Persson 1972, Persson 1975, Schneckeburger et al. 1985, Valinger and Lundqvist 1992a). During high thinnings (i.e. selective thinning from above) dominant trees are removed, which makes the remaining trees weaker and more susceptible to snow damage (Persson 1972). Trees seem especially liable to stem breakage after heavy high thinnings, when compared to unthinned stands both in Norway spruce and Scots pine stands (Persson 1972, Rottmann 1985a, Valinger et al. 1994). In general both unthinned and high thinned stands (25 % from basal area) are more liable to damage by snow than low thinned stands (Valinger et al. 1994). Stands which have undergone systematic thinning (such as row or line thinnings) also seem to be more prone to snow damage than low thinned stands (Persson 1972, Williston 1974, Shepard 1975, Valinger and Lundqvist 1992a).

Thinning grade. Samuelsson (1970) has suggested that the thinning grade does not affect the risk of snow damage if low thinning is used (which is recommended in young stands). Un-

like Samuelsson (1970), Persson (1972) and Valinger et al. (1994) have found that in low thinnings snow damage decreases with increased thinning grade, but risk of insect or fungal attacks increases. On the other hand, if weak individuals are left after light low thinning (approximately 25 % from the basal area) it is usually these weakened trees that are damaged by snow (Persson 1972, 1975). Over-stocked stands in particular should be thinned by light and frequent low thinnings (Williston 1974).

Sensitivity after thinning. Also low thinning temporarily increases the susceptibility of a stand to snow damage (Powers and Oliver 1970, Parez 1972, Abetz and Prange 1976, Schneckeburger et al. 1985). Trees are most susceptible to snow damage during the first and second years after thinning (Suominen 1963, Samuelson 1970, Persson 1972, 1975, Shepard 1975, Perttilä 1987, Valinger and Lundqvist 1992a, 1992b) but the period of enhanced risk may last for 5 years after low thinning and 8 years after high thinning (Johann 1981, Valinger and Lundqvist 1992a, 1992b, Valinger et al. 1994). On high risk sites, thinning should be repeated only a few times within a single rotation. Frequent thinnings, particularly of older stands, should be avoided, because of the disruption to the canopy and increasing risk of root rot (Samuelson 1970, Perttilä 1987).

5.4 Fertilization

The risk of snow damage can be minimized by avoiding high-risk silvicultural treatments such as combined thinning and fertilization in high risk areas (Persson 1972, Valinger et al. 1993, Valinger and Lundqvist 1994). Snow damage to trees has been found to increase by up to 100 % after fertilization (Persson 1972). This is because fertilization (e.g. with nitrogen) promotes increased growth within the crown and a greater number of long needles resulting in an increase in area available to catch rime, snow and ice (e.g. Kreuzer 1967, Schneckeburger et al. 1985, Valinger et al. 1994). Stem wood produced after fertilization may also develop less dense fibres which are less resistant to structural damage (Schneckeburger et al. 1985).

Tree crown growth increases more than stem and root diameter growth in the first few years after fertilization (Persson 1972, Pertilä 1987, Valinger 1992b). Furthermore, fertilization promotes expansion of the upper crown at first, with an increase in lower bole growth a few years later (Valinger and Lundqvist 1992b). The combination of thinning and nitrogen fertilization causes an even higher risk than fertilization or thinning alone. According to Valinger and Lundqvist (1992a, 1992b), the combined treatments lead to a prolonged period during which trees are sensitive to damage. This means that a sensitive period of 4 to 5 years after thinning or fertilization may be extended to 8 to 10 years after the combined treatment (Valinger et al. 1994). These operations and their influence on damage could lead to unscheduled thinnings in damaged stands, which may happen at inconvenient times for stand development and disrupt forest management planning and harvesting schedules. Repeated fertilizations have also been shown to increase damage (Hirvelä and Hynynen 1990).

6 Discussion and Conclusions

Within the European Community snow damage accounts 4 million m³ of timber every year, causing significant economical losses to the forest owners. Regionally the amount of snow damage can vary from breakage of a single tree to forest damage over tens of hectares (Rottmann 1985a). Such damage can force forest owners to change their forest management and incur additional costs or adopt strategies that are not optimal. Tree growth can be reduced under snow loading and the quality of timber decreased. Trees suffering crown breakage are liable to consequential damage (Valinger and Lundqvist 1994, Valinger et al. 1994).

Snow damage in forests depends on the interaction of meteorological conditions, topography, and tree and stand characteristics; the latter are controlled by management regimes and forest operations. To weigh up the relative importance of the different factors is very difficult and can lead to conflicting advice. Thus certain topographic positions may tend to be used for partic-

ular species which are managed by a particular regime; attributing the pattern of damage that results solely to e.g. species would be misleading. Cross-comparisons between countries can be very difficult because of different silvicultural practices and climatologies – hence the different elevational zones at risk in Northern and Central Europe. Different synoptic conditions can produce snow of very different moisture contents which behave differently e.g. dry snow is dislodged in modest winds, but wet snow is driven to adhere to stems in strong winds. Such conditions may be found within a single event. Snow damage is therefore a simple term that encompasses a very variable phenomena, and may include loading due to snow and freezing rain. For some events the effects are so transient as to make recording at time of damage very difficult. Researchers should therefore beware simple conclusions from patterns of damage and should also be careful to define the type of snow damage concerned. More effort should be taken to specify the mechanisms of snow accumulation, the type, amount and duration of loading, and the characteristics of the stand that affect the mechanical strength of the trees (Table 3). There is a need to further clarify the terminology of snow damage.

Stem taper and crown characteristics are the main tree characteristics which control the tree resistance to snow loading. Asymmetric crowns, stiff branches, and slender tree stems all represent high risk trees. While crown characteristics may be species or provenance dependent, taper is very dependent on silvicultural regime. Choice of regeneration method, species and provenances, site preparation, initial spacing, tending and thinning method, can decrease the risk for snow damage. For example, Valinger et al. (1993) have suggested that risk of snow damage could be reduced by as much as 40 %, if high risk trees are removed, based on simulated thinnings. This is because stem strength is strongly related to diameter and therefore highly tapered trees are most resistant. However, the means by which this taper is achieved is important, e.g. late thinning is highly vulnerable. In high risk areas it would be best to select resistant strategies but the difficulty is to specify these and to obtain an appropriate balance between risk minimisation and production potential. Many of the potential

Table 3. Factors influencing risk and type of snow damage. Possible components of a model of risk of snow damage.

Snow provision	Snow accumulation	Mechanical resistance to loading	Silvicultural practice
Geographic location	Crown structure	Branch strength	Species choice
Topographic position	Stand structure	Stem strength	Establishment
Elevation		Root anchorage	Spacing
Aspect			Thinning/cleaning
Snow type			Forest layout

strategies are costly or result in sub-optimal production from the stand; for example Garack and Schroder (1986) found that pursuing a wider spacing strategy to produce the desired taper resulted in a loss of volume of almost 10 %.

During the last few decades, it has been suggested that the apparently increasing risk of snow damage for example in Northern Europe, is due mainly to the increase in total growing stock (Valinger and Lundqvist 1994). In the future, assuming the global change in climate, both the mean temperature and precipitation could rise in northern latitudes (Kettunen et al. 1987, Carter et al. 1995), and the risk of snow damage could increase compared to the present day. This is because, the frequency of snowfalls at temperatures of around zero could increase. Thus, the snow damage risk may increase even though the relative amount of snowfall of the total precipitation would be reduced as predicted (Kuusisto 1989). Therefore, an understanding of the link between risk assessment and forest management could be more important than now in order to prevent an increase in the amount of snow damage. However, to weigh up the relative importance of the factors affecting risk of snow damage requires an objective framework, and this does not yet exist. Work is required to develop a risk model and to improve basic understanding of the processes involved. Such a model should address the process of snow accumulation, and the combined effect of wind and temperature; how the probability of the various types of snow varies within regions; the mechanisms of loading on the tree crown and stem; measures of the trees mechanical resistance to loading.

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References

- Abetz, P. & Prange, H. 1976. Schneebruchschäden vom März 1975 in einer Kiefern-Versuchsfläche mit geometrischen und selektiven Eingriffen in der nordbadischen Rheinebene. *Allgemeine Forstzeitschrift* 31(28): 583–586.

- Andersson, S.-O. 1967. Røj för mer virke. *Skogen* 54(23): 594–597.
- Armescu, S. 1973. Effect of crown breakages on increment in Norway spruce. *Revista Padurilor* 88(2): 88–92. (In Rumanian).
- Assman, E. 1970. *The principles of forest yield study*. Pergamon Press, New York. 329 p.
- Braastad, H. 1978. Report of snow and wind damage on a thinning experiment area. Norsk Institutt for Skogforskning Rep. 1/78. 54 p. (In Norwegian).
- Cannell, M.G.R. & Morgan, J. 1989. Branch breakage under snow and ice loads. *Tree Physiology* 5: 307–317.
- Carter, T., Posch, M. & Tuomenvirta, H. 1995. *Silmusen and Glingen user's guide. Guidelines for the construction of climatic scenarios and use of stochastic weather generator in the Finnish Research Programme on Climate Change (Silmu)*. 62 p.
- Chroust, I. 1965. Fichten-Dickungspflege durch starke Eingriffe bei intensivem Waldbau. *Archiv für Forstwesen* 14(6): 667–679.
- Cool, B.M. & Goebel, N.B. 1971. Glaze damage to *Pinus elliottii* and *Pinus palustris* and *Pinus taeda* in Sandhills area of South Carolina. *Clemson University, Forest Research Series* 21. 14 p.
- Cremer, K.W. 1983. Snow damage in Eucalypt forests. *Australian Forestry* 46(1): 48–52.
- , Carter, P.R. & Minko, G. 1983. Snow damage in Australian pine plantations. *Australian Forestry* 46(1): 53–66.
- Curtis, J.D. 1936. Snow damage in plantations. *Journal of Forestry* 34: 613–619.
- Dittrich, K. 1989. Das forstliche Shadgeschehen in Spiegel der Langzeitstatistik – naturbedingt abiotisches Schadegeschehen. *Sozialistische Forstwirtschaft* 39: 84–88.
- Ffolliot, P.F. & Thompson, J.R. 1976. Snow damage in Arizona ponderosa pine stands. USDA Forest Service, Rocky Mountain Forest and Range Experimental Station, Research Note RM 332. 2 p.
- Frank, H. 1948. Snow damage of the winter 1946–47. *Forestry Commission Journal* 19, 98.
- Furuno, T. & Watanabe, H. 1970. The relationship of damage to *Pinus pinaster* by snow and shoot moth, *Dioryctia splendellia*. *Bulletin of the Kyoto University Forests* 41: 41–55. (In Japanese).
- Garack, S. & Schroder, I. 1986. Stabilität und Produktivität eines durch Schnee geschädigten Fichtenbestandes. *Beiträge für die Forstwirtschaft* 20(1): 27–30.
- Gardiner, B.A., Stacey, G.R., Belcher, R.E. & Wood, C.J. 1997. Field and wind tunnel assessments of the implications of respacing and thinning for tree stability. *Forestry*. (In press).
- Gill, D. 1974. Snow damage to boreal mixedwood stands in northern Alberta. *Forestry Chronicle* 50(2): 70–73.
- Goebel, N.B. & Deitschman, G.H. 1967. Ice storm damage to planted conifers in Iowa. *Journal of Forestry* 65(7): 496–497.
- Guild, D.W. 1986. Snow damage in Otago and Southland. *New Zealand Journal of Forestry* 31(2): 9–14.
- Hall, C.S. 1967. Some mechanical and nutritional aspects of cambial increment distribution in red pine. Ph.D. thesis. Yale University, School of Forestry, U.S.A.
- Haring, P. & Iugu, M. 1970. Studies on snow breakage in Norway spruce stands of mountains of the Mammures. *Stud. Cerc. Inst. Cerc. Silvica*. 27(2): 479–499.
- Heikinheimo, O. 1920. Suomen lumituhouluet ja niiden metsät. Referat: Die Schneeschadengebiete in Finnland und Ihre Wälder. *Communicationes Instituti Forestalis Fenniae* 3(3). 133 p. (In Finnish).
- Hirvelä, H. & Hynynen, J. 1990. Effect of fertilisation on the growth, top damage and susceptibility to windthrow of Scots pine stands in Lapland. *Folia Forestalia* 764. 16 p.
- Hoover, M.D. & Leaf, C.F. 1967. Process and significance of interception in Colorado subalpine forest. In: *Sopper, W.E. & Lull, H.W. (eds.). Forest hydrology*. Pergamon, New York. p. 213–224.
- Jackson, M.C. 1977. A method for estimating the probability of occurrence of snow water equivalents in the United Kingdom. *Hydrological Sciences Bulletin* 22: 127–142.
- Johann, K. 1981. Nicht Schnee, sondern falsche Bestandsbehandlung verursacht Katastrophen. *Allgemeine Forstzeitung* (92): 163–171.
- Jones, H.G. 1983. *Plants and microclimate. A quantitative approach to environmental plant physiology*. Cambridge University Press, Cambridge. 323 p.
- Juutinen, P. 1953. Männyn toipuminen Kolilla talven 1947–48 lumituhojen jälkeen. Deutsches referat: Die Erholung der Kiefer auf der Koli-anhöhe nach den Schneebruchschäden im Winter 1947–48. *Communicationes Instituti Forestalis Fenniae* 41(2). 43 p. (In Finnish).
- Kalela, A. 1937. Zur Synthese der experimentellen

- Untersuchungen über Klimarassen der Holzarten. *Communicationes Instituti Forestalis Fenniae* 26. 445 p.
- Kangas, E. 1959. Lumenmurot ja metsänhoito. Metsätaloudellinen aikakauslehti 1. 3 p. (In Finnish).
- Kangur, R. 1973. Snow damage to young Western hemlock and Douglas fir. Oregon State University, School of Forestry, Research Papers 21. 11 p.
- Keller, H.M. 1979. Snow cover in forest stands. In: Mountain forests and avalanches; proceedings of the IUFRO working party on Snow and avalanches, Davos, September 1978. SFISAR, Berne. p. 17–29.
- Kettunen, L., Mukula, J., Pohjonen, V. & Varjo, U. 1987. The effect of climatic variations on agriculture in Finland. In: Parry, M.L., Carter, T.R. & Konjin, T.N. (eds.). The impact of climatic variations on agriculture. Volume 1. Assessments in cool temperate and cold regions. International Institute for Applied Systems Analysis. 90 p.
- Kramer, H. 1975. Erhöhung der Produktionssicherheit zur Förderung einer nachhaltigen Fichtenwirtschaft. *Forstarchiv* 46(1): 9–13.
- Kreutzer, K. 1967. Ernährungszustand und Volumenzuwachs von Kieferbeständen neuer Dungungsversuche in Bayern. *Forstwissenschaftliches Centralblatt* 86: 28–53.
- Kunze, M. 1897. Über den Einfluss der Anbaumethode auf den Ertrag der Fichte. *Thar. Forstl. Jahrbuch* (47): 25–89.
- Kuusisto, E. 1989. Lumi ja jää – uusiutumattomia luonnonvaroja tulevaisuudessa? *Vesitalous* 5/1989: 2–5. (In Finnish).
- Lavers, G.M. 1969. The strength properties of timbers. 2nd edition. *Forest Products Research Laboratory Bulletin* 50. 62 p.
- Lear, D.H. van & Saucier, J.R. 1973. Comparative glaze damage in adjacent stands of Slash and Longleaf pine. *Clemson University, Forest Research Series* 27.
- Lines, R. 1980. Stability of *Pinus contorta* in relation to wind and snow. *Pinus contorta* as an exotic species. *Proceedings of IUFRO Working party Meeting*. p. 209–219.
- 1996. Experiments on lodgepole pine seed origins in Britain. *Forestry Commission Technical Paper* 10. Forestry Commission, Edinburgh.
- Matthews, J.D. 1989. *Silvicultural systems*. Oxford. 284 p.
- Megahan, W.F. & Steele, R. 1987. An approach for predicting snow damage to ponderosa pine plantations. *Forest Science* 33(2): 485–503.
- Mergen, F. & Winner, H.I. 1952. Compression failures in boles of living conifers. *Journal of Forestry* 50: 677–681.
- Merkel, O. 1975. Schneebruch im Fichtenbestand bei 40jähriger Auslesedurchforstung. *Allgemeine Forstzeitschrift* 30(33/34): 663–665.
- Mikola, P. 1938. Kuusen latvus- ja runkomuodosta Maanselän lumituoalueella. Referat: Über die Kronen- und Schaftform der Fichte im Schneeschadengebiet von Maanselkä in Ost-Finnland. *Silva Fennica* 47: 1–36. (In Finnish).
- Miller, D.H. 1964. Interception processes during snowstorms. U.S. Forest Service, Pacific Southwest Forest Range Experimental Station, Research Paper PSW 18. 24 p.
- Mindler, H. 1967. Resistance of young spruce stands to atmospheric influences. *Sozialistische Forstwirtschaft* 17(2): 57–59. (In German).
- Nicholas, N.S. & Zedacker, S.M. 1989. Ice damage in spruce-fir forests of the Black Mountains, North Carolina. *Canadian Journal of Forest Research* 19: 1487–1491.
- Norokorpi, Y. 1981. Lakimetsien rajaamisen perusteita. *Metsäntutkimuslaitoksen tiedonantoja* 24: 59–65. (In Finnish).
- 1994. Havumetsärajan sijainnin määräytyminen Suomessa. In: Tasanen, T., Varmola, M. & Niemi, M. (eds.). 1994. *Metsänraja tutkimuksen kohteena. Metsäntutkimuslaitoksen tiedonantoja* 539: 7–15. (In Finnish).
- & Kärkkäinen, S. 1985. Maaston korkeuden vaikutus puusto- ja kasvupaikatunnuksiin sekä tykkytuhoihin Kuusamossa. Summary: The effect of altitude on stand and site characteristics and crown snow-load damages Kuusamo in Northern Finland. *Folia Forestalia* 632. 26 p. (In Finnish).
- Parez, J. 1972. The effect of low thinning and crown thinning on the extent of snow damage in stands on thinning sample plots over the period 1959–68. *Lesnictvi* 18(2): 143–154.
- Peltola, H. & Kellomäki, S. 1993. A mechanistic model for calculating windthrow and stem breakage of Scots pines at stand edge. *Silva Fennica* 27(2): 99–111.
- , Nykänen, M-L. & Kellomäki, S. 1997a. Model computations on the critical combination of snow loading and windspeed for snow damage of Scots pine, Norway spruce and birch sp. at stand edge.

- Forest Ecology and Management. (In press).
- , Kellomäki, S. & Väisänen, H. 1997b. Model computations on the impacts of climatic change on soil frost with implications for windthrow risk of trees. *Climate Change*. (Accepted).
- Persson, P. 1972. Vind- och snöskadors samband med beståndsbehandlingen – inventering av yngre gallringsförsök. Skogshögskolan, Institutionen för skogsproduktion, Rapporter och Uppsatser 23. 205 p. (In Swedish).
- 1975. Stormskador på skog – uppkomstbetingelser och inverkan av skogliga åtgärder. Skogshögskolan, Institutionen för skogsproduktion, Rapporter och Uppsatser 36. 294 p. (In Swedish).
- Perttälä, P. 1987. Myrsky- ja lumituhojen esiintymisen sähkölinjoilla. Inventointi ja käsittelyohjeet. Metsänarvioimistieteen pro gradu-tutkielma. Helsingin yliopisto. 63 p. (In Finnish).
- Petty, J.A. & Worrell, R. 1981. Stability of coniferous tree stems in relation to damage by snow. *Forestry* 54(2): 115–128.
- & Swain, C. 1985. Factors influencing stem breakage of conifers in high winds. *Forestry* 58(1): 75–85.
- Powers, R.F. & Oliver, W.W. 1970. Snow breakage in a pole-sized ponderosa pine plantation, more damage at high stand-densities. USDA Forest Service, Research Note PSW 218. 3 p.
- Quine, C.P. 1995. Assessing the risk of wind damage to forests: practice and pitfalls. In: Coutts, M.P. & Grace, J. (eds.). *Wind and trees*. Cambridge University Press, Cambridge. p. 379–403.
- , Burnand, A.C., Coutts, M.P. & Reynard, B.R. 1991. Effects of mounds and stumps on the root architecture of Sitka spruce on a peaty gley restocking site. *Forestry* 64: 385–401.
- , Coutts, M.P., Gardiner, B.A. & Pyatt, D.G. 1995. Forests and wind: management to minimise damage. *Forestry Commission Bulletin* 114.
- Rendle, B.J., Armstrong F.H. & Nevard, E.H. 1941. Utilization of softwood timber damaged by glaze. *Forestry* (15): 55–63.
- Rottmann, M. 1985a. Schneebruchschäden in Nadelholzbeständen. Beiträge zur Beurteilung der Schneebruchgefährdung, zur Schadensvorbeugung und zur Behandlung schneegefährdeter Nadelholzbestände. J.D. Sauerländer's Verlag, Frankfurt am Main. 159 p.
- 1985b. Waldbauliche Konsequenzen aus Schneebruchkatastrophen. *Schweizerische Zeitschrift für Forstwesen* 136(3): 167–184.
- 1986. Wind- und Sturmschäden im Wald. Beiträge zur Beurteilung der Bruchgefährdung, zur Schadensvorbeugung und zur Behandlung sturmeschädigter Nadelholzbestände. J.D. Sauerländer's Verlag, Frankfurt am Main. 128 p.
- Rummukainen, U. 1967. Damage caused in 1947 and 58/59 by heavy snowfall following glaze storms. *Finn. Pap. Timb.* 18(3): 17–19. (In Finnish).
- Saeki, M. & Sugiyama, T. 1965. Danger zone in snow damage to forest trees by the snow crown. *Bulletin of Forest Experimental Station, Meguro Tokyo* 172: 117–137. (In Japanese).
- Sampson, G.R. & Wurtz, T.L. 1994. Record interior Alaska snowfall effect on tree breakage. *Northern Journal of Applied Forestry* 11(4): 138–140.
- Samuelson, E. 1970. Storm och snö i skogen. *Skogsägaren* 12: 17–19.
- Sanzen-Baker, R.G. & Nimmo, M. 1941. Glazed frost 1940 – damage to forest trees in England and Wales. *Forestry* 15: 38–54.
- Satterland, D.R. & Haupt, H.F. 1967. Snow catch by coniferous crowns. *Repr. Water Resour. Res.* Wash 3(4): 1035–39.
- Schmidt, R.A. & Pomeroy, J.W. 1990. Bending of a conifer branch at subfreezing temperatures: implications for snow interception. *Canadian Journal of Forest Research* 20(8): 1250–1253.
- Schmidt, W.C. & Schmidt, J.A. 1979. Recovery of snow-bent young western larch. USDA Forest Service, Intermountain Forest and Range Experiment Station, General Technical Report INT-54, 13 p.
- Schneckenburger, F., Brown, K.M. & Barker, J.E. 1985. Effects of nitrogen fertilization and low thinning on snow damage in jack pine. *Forest Science* 31(3): 552–556.
- Schöpfer, W. 1964. Schneebruchschäden – einmal anders gesehen. *Allgemeine Forstzeitung* 19(5): 66–70.
- Schroeder, L.M. & Eidmann, H.H. 1993. Attacks of bark- and wood-boring Coleoptera on snow-broken conifers over a two-year period. *Scandinavian Journal of Forest Research* 8: 257–265.
- Schubert, G.H. 1971. Growth response of even-aged ponderosa pines related to stand density levels. *Journal of Forestry* 69(12): 857–860.
- Shepard, R.K. 1975. Ice storm damage to loblolly pine in northern Louisiana. *Journal of Forestry* 73(7): 420–423.

- Slodiacák, M. 1995. Thinning regime in stands of Norway spruce subjected to snow and wind damage. In: Coutts, M.P. & Grace, J. (eds.). *Wind and trees*. Cambridge University Press. p. 436–557.
- Solantie, R. & Ahti, K. 1980. Säätekijöiden vaikutus Etelä-Suomen lumituhoihin v. 1959. Summary: The influence of weather in the snow damages for forests of South-Finland in 1959. *Silva Fennica* 14(4): 342–353. (In Finnish).
- 1974. Pohjois-Suomen lumipeitteestä. Summary: On snow cover in northern Finland. *Lapin ilmasto-kirja, Climate of Lapland*. Lapin tutkimusseura. p. 74–89. (In Finnish).
- 1994. Effect of weather and climatological background on snow damage of forests in southern Finland in November 1991. *Silva Fennica* 28(3): 203–211.
- Steiner, J. 1975. Zur Gefährdung von Kiefernjungbeständen durch atmosphärische Einwirkungen nach selektiven und schematischen Eingriffen. *Beiträge für die Forstwirtschaft* 9(4): 172–174.
- Sugiyama, T. & Saeki, M. 1963. Survey of snow damage in the Hokuriko prefecture by the snowfall of Dec. 1960. *Bulletin of Forest Experimental Station, Meguro Tokyo* 154: 73–95. (In Japanese).
- Suominen, O. 1963. Metsiköiden alttius lumituhoon. Tutkimus Etelä-Suomessa talvella 1958–59 satuneesta lumituhosta. Summary: Susceptibility of stands to devastation by snow. Investigation into snow devastation in South Finland in winter 1958–59. *Silva Fennica* 112(5): 1–35.
- Valinger, E. & Lundqvist, L. 1992a. En analys av snöbrottsskador på Örnsköldsviks skogsförvaltning, MoDo. Sveriges lantbruksuniversitet, Institutionen för skogskötsel, Arbetsrapporter 64. 22 p.
- & Lundqvist, L. 1992b. The influence of thinning and nitrogen fertilisation on the frequency of snow and wind induced stand damage in forests. *Scottish Forestry* (46): 311–320.
- , Lundqvist, L. & Bondesson, L. 1993. Assessing the risk of snow and wind damage from tree physical characteristics. *Forestry* 66(3): 249–260.
- & Lundqvist, L. 1994. Reducing wind and snow induced damage in forestry. Sveriges lantbruksuniversitet, Institutionen för skogskötsel, Rapporter 37. 11 p.
- , Lundqvist, L. & Brandel, G. 1994. Wind and snow damage in a thinning and fertilisation experiment in *Pinus sylvestris*. *Scandinavian Journal of Forest Research* 9: 129–134.
- Wakabayashi, R. 1979. Deformation and damage to forest plants by snow forces. Mountain forests and avalanches; Proceedings of the IUFRO Working Party on Snow and Avalanches, Davos, September 1978. SFISAR, Berne. p. 205–209.
- Watson, F. 1936. Snow damage in a conifer area. *Forestry Commission Journal* 15. 68 p.
- Williston, H.L. 1974. Managing pines in the ice-storm belt. *Journal of Forestry* 72(9): 580–582.
- Wooldridge, G.L., Musselman, R.C., Sommerfeld, R.A., Fox, D.G., & Connel, B.H. 1996. Mean wind patterns and snow depths in an alpine-subalpine ecosystem as measured by damage to coniferous trees. *Journal of Applied Ecology* 33: 100–108.
- Worrell, R. 1979. Snow damages to the stems of coniferous trees. Unpublished Honours Degree Thesis. Forestry Department, University of Aberdeen. 132 p.
- Wright, J.A. & Quine, C.P. 1993. The use of a Geographical Information System to investigate storm damage to trees at Wykeham Forest, North Yorkshire. *Scottish Forestry* 47(4): 166–174.

Total of 102 references