MINIMIZING WIND DAMAGE IN ALTERNATIVE SILVICULTURE SYSTEMS IN BOREAL MIXEDWOODS

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DISCLAIMER

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ABSTRACT

The nature of wind damage in forest stands is reviewed and related to the silvicultural systems used or being developed for management of Boreal mixedwoods. The approaches for minimizing wind damage in released white spruce understory specific to the two-stage harvesting and silvicultural system are given detailed consideration. The review addresses the individual tree stability, stand stability and external stability factors such as site, topography, windiness of the region and sheltering effect of adjacent stands and relates these to a framework for recognizing high risk sites and stands. Principles of wind damage management are discussed in the context of designing silvicultural systems with incremental wind protection levels.

ACKNOWLEDGEMENTS

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A.   INTRODUCTION

Wind damage in managed forest stands is a major source of economic loss, and is steadily increasing in many parts of the world. One of the reasons for increasing losses is the change from conditions of natural stands brought on by management and silvicultural practices and by intensification of forestry practice.

In Boreal forests of western Canada, the demands on management of forest resources have changed considerably over the last 40 years (Brace 1993). As we attempt to accommodate more diversified demands, silvicultural objectives become more complex and more silvicultural options need to be explored. One of the results of this trend is a renewed interest in alternative silvicultural systems.

The difficulty is that a greater array of silvicultural options require increased complexity in forest protection. Wind damage risk and its management is one such complexity that must be addressed in the choice and design of silvicultural systems.

The objectives of this report are to first provide basic knowledge and principles of wind damage management to assist in planning and implementing silvicultural systems which will prevent or reduce major future losses in the Boreal forest, and secondly, to apply the basic knowledge and principles for wind damage protection of released understory white spruce when developing silvicultural prescriptions.

In boreal hardwood and hardwood-softwood stands with white spruce overstory, a silvicultural and harvesting system that protects understory spruce while harvesting an aspen overstory is a viable management option gaining increasing application in Boreal mixed woods (Brace Forest Services 1992, Sauders 1992). Wind damage risk in released spruce after the removal of aspen has been identified as the major constraint to wide application of this silvicultural option (Navratil et al. 1994).

Windthrow involves complex interactions between many factors, including stand development which influences tree stability, site conditions which influence tree anchorage, and topography and stand structure which cause highly variable wind conditions. Hence wind behavior and windthrow in forests is highly unpredictable.

Due to the great diversity in forests and the complexity of wind damage, caution should be used when taking relationships derived in one location and applying them to another. This report is intended to serve as a source of information, not as an explicit guideline for application of wind protection measures.

A preliminary version of this report was prepared in 1992 for the Alberta White Spruce Understory Committee as background for Canada-Alberta Partnership Agreement Project 8032, which was planned to test the effectiveness of several silvicultural and harvesting designs for reducing wind damage to immature released white spruce (Navratil et al. 1994).

A recent review of windthrow problems, published in British Columbia (Stathers et al. 1994), provides information which is complementary to this report.

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B.   TYPES OF WIND DAMAGE TO FOREST TREES

Eight broad types of wind damage are noted. The first four are those that occur most frequently in managed forest stands.

1.   Windbreak

Windbreak, which refers to stem breakage, occurs when the windload (the pressure exerted by the wind) is greater than the breaking stress of wood. It usually occurs after brief windloads of great force. Trees with low taper are more liable to break.

2.   Windthrow

If the stem strength is greater than the windload the tree does not break but it uproots and topples over. However, if the soil is frozen, wind damage occurs in the form of wind break. In contrast, the moister the soil, the greater the probability of windthrow.

Windthrow is by far the most prevalent type of damage observed in released white spruce understory. Consequently tree and stand stability components related to windthrow are examined and discussed in more detail.

3.   Leaning and Bending

Leaning and bending can be considered intermediate or light stages of windbreak and windthrow.
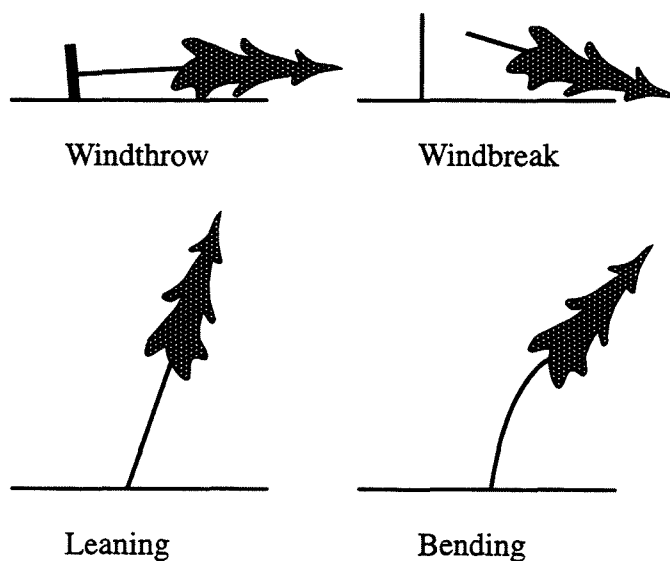
Figure 1.   Four common types of wind damage.

Other types of damage and loss caused by wind are rarely quantified and frequently poorly recognized:

4. Early toppling

Early toppling and subsequent butt sweep has been observed in planted trees (Burdett et sl. 1986). Similar butt sweep may be observed in white spruce understory trees that have recovered from leaning induced during harvest.

5. Stem deformation and reduced wood quality

This can result from leader loss and changes in wood properties, including formation of reaction wood.

6. Growth reduction

Root damage and loss of foliage caused by wind may cause reductions in growth

7. Invisible damage with delayed effects

Tension and compression stresses in the stem and roots caused by tree swaying will damage cambium and fine roots and frequently result in fungal infections and insect infestations.

C. DAMAGING WIND SPEEDS

The Beaufort scale classifies winds into 12 categories and provides a guide for wind characterization in forestry applications. The scale combines wind pressure and wind speed to help categorize potential for damage. Categories that cause damage in forest stands (categories 6-12) are shown in Figure 2.
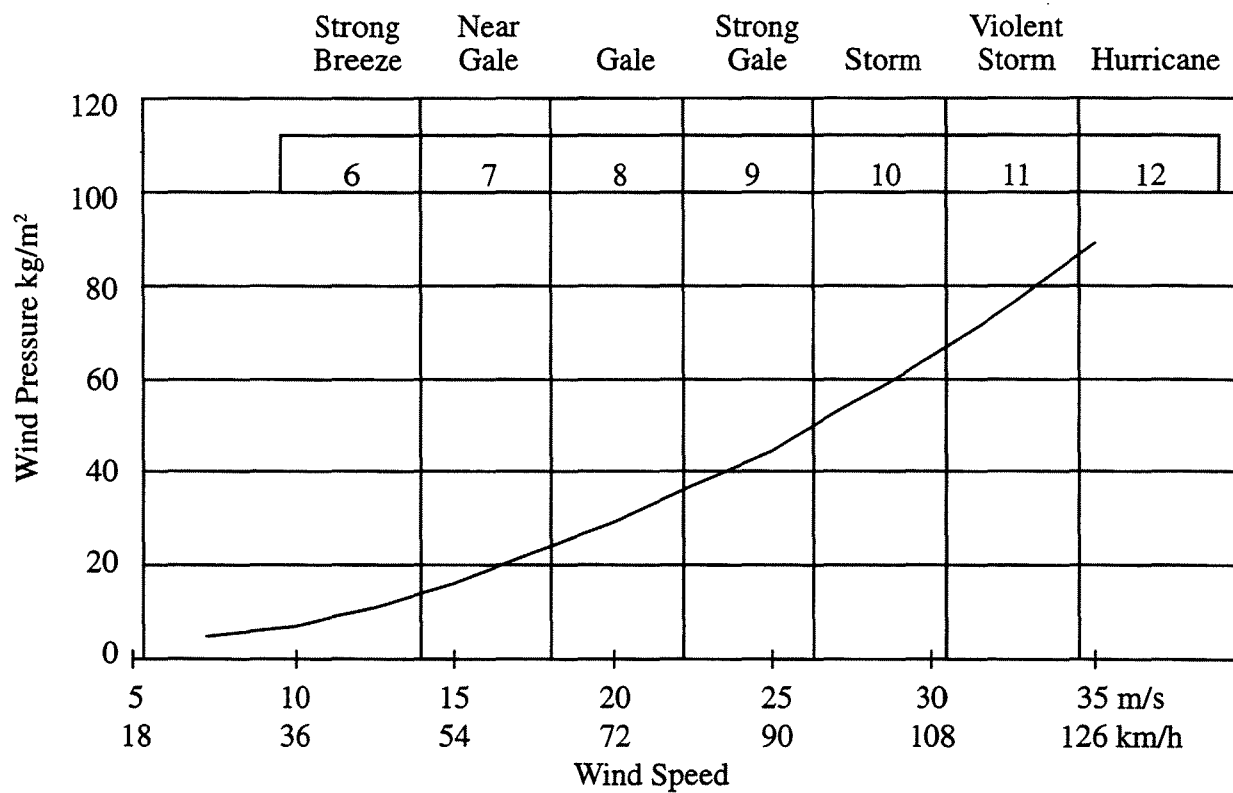
Figure 2.   Beaufort scale and windspeeds damaging forest trees and stands.

1.   Low Speed Winds

Wind is a potent ecological factor affecting growth and form of trees even at moderate speeds. Winds with speeds of 25-50 km/hour can cause malformation and growth reduction due to breakage of tender leaders. Constant exposure of lodgepole pine to 30 km/hour winds reduced extension of leaders by 20% (Rees and Grace 1980). The effects of low speed winds on white spruce understory are unknown. The beneficial influence of frequent low speed winds in stimulating the growth of root systems likely outweighs potential losses due to breakage of leaders and crown deformation.

2. Winds With Speeds 60-90 Km/Hour—Endemic Damage

Damage to trees starts at wind speeds over 60 km/hour (16.6 m/sec) when pressure exceeds 25 kg/m^2 (corresponds to class 8 on the Beaufort scale). Winds of this speed move large trees and break off foliated branches.

Wind speeds 66-75 km/hour (class 9 on the Beaufort scale) break thin and unstable trees, break off dry and non-foliated branches, and strongly oscillate trees of all sizes. Strong gales with wind speeds 78-90 km/hour break and topple large trees.

Because of their relative frequency, winds in all of the above categories are of most concern to the forest manager. The damage that results can be cumulative, causing steady or incremental stand deterioration over time.

Endemic windthrow arises as a result of winds with moderate speeds of 72 km/hour (20 m/sec) and associated gusts of higher wind speeds (Miller 1985). Where stand structure and tree wind resistance has been altered by harvesting or silvicultural treatments, devastating endemic wind damage may occur at any time. In addition to stand and tree conditions, this type of damage and its incidence is strongly influenced by site. Control measures to limit the extent of endemic wind damage can be built on its strong relationship to the stand, tree and site conditions.

The approach in spruce understory protection can involve stand and site evaluation and stand treatments applied prior to aspen canopy removal and stand treatments applied after aspen canopy removal.

In many areas of Alberta, winds of speeds over 72 km/hour (20 m/sec) return on a yearly basis. For this reason alone, the likelihood of frequent windthrow in released white spruce is very high. Control measures should be aimed at this category of frequently occurring winds.

3. Catastrophic Windstorms

Wind speeds over 100 km/hour, violent storms and hurricanes cause catastrophic damage to forests. A sustained 90+ km/hour wind damages trees and stands under almost any stand, site and soil conditions. No tree species can survive without damage a violent storm with mean wind speeds higher than 108 km/hour (30m/sec) over a period of 10 minutes (Mayer 1989).

From a forest management viewpoint, very little can be done to prevent losses from major catastrophic storms. Some loss is inevitable and should be factored into Annual Allowable Cut (AAC) calculations according to wind history and conditions of the stands.

Catastrophic storms usually devastate a small area and recur at intervals which vary by geographic region. In some parts of the world the recurrence interval for large-scale storms is relatively short. In New Zealand, for example, it may be as little as 10 years. In contrast, the period of large-scale windthrow in northeast Maine was estimated to be longer than several rotations (Lorimer 1977).

Recurrence intervals of large-scale storms are extremely important to risk calculations and forest management planning. Where short recurrence intervals of high speed winds are observed, forest management planning should increase the diversity of stand ages and heights and reduce the proportion of silvicultural systems that create wind risk situations.

4. Gusts and Turbulence

Wind speeds fluctuate irregularly between minima (lulls) and maxima (gusts). The wind speed changes 30-60% and sometimes over 300%. These fluctuations are caused by turbulence and are greater at higher wind speeds. Any surface exerts a drag on the air stream and any protrusion from the surface produces a turbulent wake on the lee side. Eddies resulting from this turbulence are very effective at transferring energy onto standing trees. It is generally accepted that windthrow is more affected by the turbulence component of wind structure than by pure linear velocity (Bull and Reynolds 1968).

In forests, turbulence is affected by topography and stand conditions. For example, when wind hits a dense stand edge, it is deflected upwards and strikes more swiftly moving currents in the air layers above the stand canopy. The resulting turbulence may not endanger the sturdy stand edge trees, but may damage the unstable trees behind them (Figure 3). An uneven stand canopy and stand structure (such as large trees above the surface of stand) can also increase turbulence. Similarly, very dense, large groups or clumps of trees, particularly if they are located on higher positions or opposite large gaps and openings, may contribute to air flows resulting in higher speed and turbulence. It is recognized that turbulence is an extremely complex and random phenomenon in forests; in general, the higher the wind speeds and the rougher the forest canopy aerodynamically, the greater the degree of turbulence (Savill 1983).

Topographic features that affect wind acceleration and turbulence are discussed in Sections G.2 and G.3.

a	b	c
Narrow spacing	Wide Spacing	Narrow spacing with high pruning of border trees
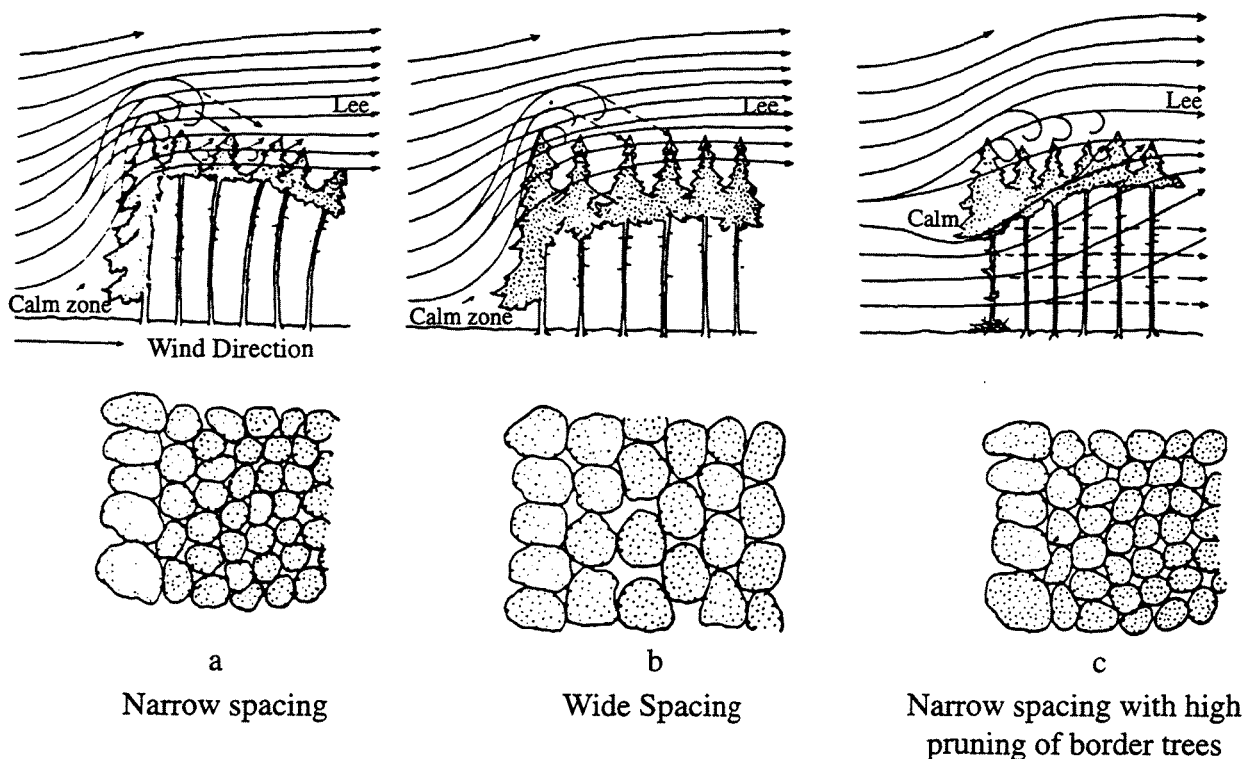
Figure 3.   Windflow and eddies in three types of stand edges (after Rottman 1986).

It is the gustiness of wind (dynamic windloads) rather than the mean wind speed which is mainly responsible for damage to trees. Gusts with the frequencies that correspond to the natural sway cycle of a tree are most likely to cause windthrow. This refers to gusts that occur when the tree is at the maximum lean in the direction of the wind. In contrast, windbreak is more frequently caused by the impact loading by gusts hitting the tree on its backward swing; if the tree does not break, damping of the sway is produced. Subsequently the tree often sways in the direction of the windload. In gusty winds sways are irregular, can even be perpendicular to wind direction and can be enhanced by asymmetry of crown and root system.

Swaying of trees, particularly swaying amplitude, is of great importance for windthrow. When trees are swaying within a stand the contact with neighboring trees has a supporting effect, i.e., swaying amplitudes become reduced.

Extensive investigations of physical fundamentals of wind-induced tree sway done in Britain (Mayhead 1973), in Germany (Mayer 1985, Mayer 1987, Mayer 1989) and elsewhere concluded that dynamic wind conditions are more important than stationary windloads. One consequence of dynamic windloads is the so-called pump effect of trees, especially of spruce (Norway spruce in the reference), which decreases friction between roots and soils and consequently reduces the windload necessary to cause damage (Mayer 1989).

Prolonged gustiness progressively lessens the anchoring strength of the roots and cohesion of the root plate to the soil. Extensive windthrow was attributed to the occurrence of prolonged, moderately fast winds with gusts over 50 km/hour and aggregate wind runs exceeding 800 km in a few days (Cremer et al. 1977). Similar weakening of tree anchorage and high damage by prolonged gusts was described on wet soils (Hütte 1968) (see Section G.4). This loosening of root plate (root-soil plate) after the occurrence of prolonged periods of gusty winds of moderate speeds is a potential source of windthrow damage for shallow-rooted white spruce especially on sites with elevated water table after harvesting.

D.   WIND STABILITY OF STANDS AND INDIVIDUAL TREES

In principle, the relationships of wind damage and tree and stand stability are very intricate, depending on many factors. Figure 4 illustrates the main relationships and components involved.

EXTERNAL STABILITY

- Site
  - topography
  - soil
  - water table

- Arrangement of surrounding stands
  - spatial (horizontal and vertical)
  - temporal

- Compartmentalization of forest landscape, dividing lines

INDIVIDUAL TREE STABILITY

- Tree morphology
  - height
  - size and form of crown
  - size and form of stem
  - size and form or root system
  - age
  - stem and root rots

- Mutual support by neighboring trees

FOREST STAND STABILITY

- Individual tree stability

- Stand structure as a consequence of stand development and treatments
  - spacing
  - canopy closure
  - quality of stand edges
  - species composition

- Reduction in wind speed by stand structure

- Protection by adjacent stands

Figure 4.   Wind stability of forest stands and individual trees.

The occurrence of wind damage in a forest stand depends on the wind and on the dynamic response of the stand. The response of the stand, i.e., whether or not the stand survives with an acceptable level of damage, is controlled by stand stability, which in turn is governed by individual tree stability, stand structure and protection by surrounding stands.

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E.   INDIVIDUAL TREE STABILITY—RESISTANCE TO WINDTHROW

Windthrow is generally the result of both stationary and turbulent windload on trees. The stationary component is related to the wind speed around a tree crown. The dynamic, turbulent windload is very complex and related to fluctuations in the wind speed and swaying (oscillation) of the tree. At present, the predictability of windthrow using modeling approaches is very low and has not yet reached a "practical" state (Mayer 1989).

Regardless of wind speed and the complexity of tree motion in response to windload, trees are subjected to different wind pressure according to their above-ground form. The load on the tree is a function of stem and crown form. If the stem strength is greater than the load pressure exerted by the wind, the tree does not break but it uproots. This occurs when the critical load on a tree surpasses the the forces anchoring the tree.

The most important tree attributes influencing individual tree stability are: size, shape and strength of the root system; size, shape and permeability of the crown; tree height and stem forms.

1.   Root System

The limiting factor of tree stability is its root system—particularly its development and strength on the lee side of the tree.

The root system of trees growing under windy conditions develops in the shape of an ellipse with the longitudinal axis in the direction of wind. The swaying of a tree in the wind causes a compressive stress on the lee side lateral roots (Busby 1966). The tree reacts to this stimulus by producing a greater number and larger size of lateral roots in this part of the root system. If the stimulus persists, trees have a remarkable ability to develop supporting roots.

Trees which grow in exposed areas such as stand edges or in widely-spaced stands build up resistance to winds from the prevailing wind direction.

Coutts (1983) described the different forces and behaviors of root-soil systems on the windward and lee sides of a tree when subjected to wind force. On the lee side, the root-soil system is subjected to bending and compressive forces against the bearing surface of the soil below, whereas on the windward side, where the root-soil plate is lifted, the system is subjected to tensile and possibly shearing forces.

With respect to root morphology, the components of root anchorage include: dimension and mass of root system; tensile strength of roots below the root-soil plate and on the windward perimeter; and the size and stiffness of the roots on the lee side. The lee side of the root-soil plate acts as a cantilevered beam and physical laws defining reduced stiffness indicate the importance of the number, size, distribution and branching of the roots on the lee side.

Figure 5 depicts the major contributors to tree stability on the windward and lee sides based on interpretations of windthrow studies in Norway spruce stands (Vicena et al. 1961). Over half of the tree stability (57%) is controlled by the strength of roots at the breaking points on the lee side. These breaking points generally occur in one third of the longitudinal half-axis of the root plate on the lee side.

Wind direction
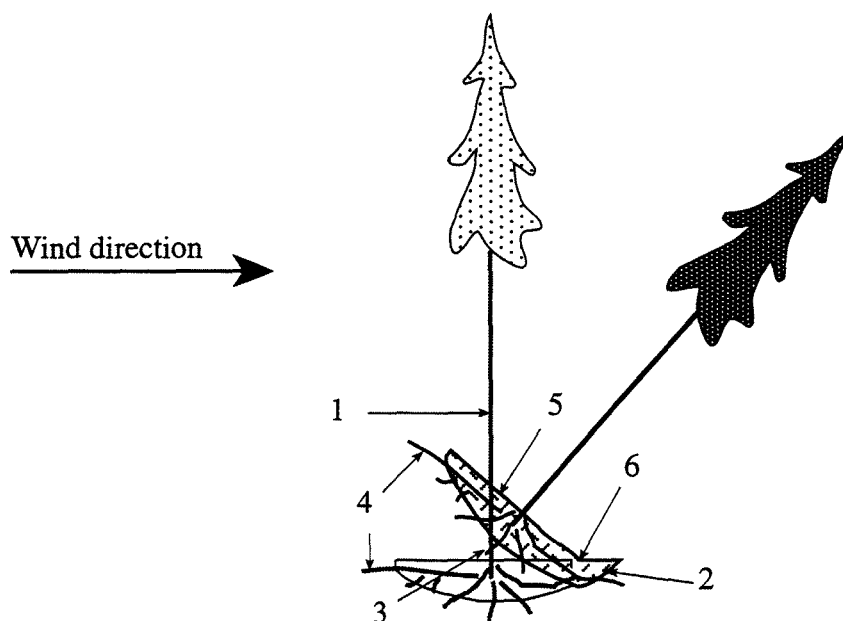
1. Mass of crown and stem   1%
2. Mass of unlifted root-soil plate   2%
3. Mass of lifted root-soil plate   7%
4. Strength of horizontal roots on the   9%
edge of root-soil plate
5. Strength of vertical roots on the   24%
bottom edge of root-soil plate
6. Strength of horizontal root on the lee   57%
side of root-soil plate

Additional resistance (not shown) arises from soil tensile strength around the edge and beneath the root-soil plate.

Figure 5.   The components influencing tree resistance to windthrow (After Vicena et al. 1961).

The roots on the windward side are also important for stability, but to a lesser degree. Tree roots are stronger in tension than in compression and therefore could keep a tree from falling provided that the roots go deep and are firmly anchored. In many coniferous tree species, including white spruce, vertical rooting is very shallow. In Norway spruce, anchoring by short vertical roots provides about 25% of tree stability (Figure 5). Tree species such as fir or pine with vertical roots or main roots that extend deeply are damaged mainly by windbreak, rather than windthrow (Mayer 1989).

A general relationship of rooting depth to windthrow occurrence has been found in several studies (e.g., Horton 1958). For some species, vertical root development may be more important than lateral development. This is shown, for example, in windfirmness studies of planted *Pinus radiata* in New Zealand (Somerville 1979). Soil classes based on rooting depth are used in wind risk classification systems in Great Britain (Miller 1985). Rooting depth cannot, however, substitute for the lack of strengthened roots on the lee side. For this reason the correlation between depth of rooting and windfirmness is not always clear and is confounded by soil and site conditions (see Section G.4) that dominate root development and root morphology.

Soil conditions which limit rooting depth are: shallow soils; wet soils; imperfectly drained or wet soils after heavy rainfalls or spring thaw; and fluctuating water table or elevated water table associated with harvest. Excessive soil moisture may critically influence the windfirmness of white spruce and may be a decisive factor in selecting stands and silvicultural systems for protection of white spruce understory.

2.   Crown Form and Stability

Tall trees are more vulnerable to windthrow than short ones because wind speed and wind drag forces increase with the distance from the ground. It is, however, a combination of tree height, crown form and crown size that determine the critical thresholds of stability of individual trees.

Crown shape in forest stands is controlled by the intensity and quality of light reaching each tree. Closed-canopy stands are characterized by "high shade" (shading by an upper canopy) and "side shade" (shading by neighbor trees of the same strata).

Crown growth response of trees growing under high shade will depend on relative shade tolerance. Shade tolerant trees, like white spruce, can grow relatively well under conditions of high shade, but in the extreme, will develop broad, flat, umbrella-like crowns.

Suppression of height growth and the associated crown shape resulting from high shade (e.g., from aspen overstory) can be accentuated when combined with side shade (e.g., from neighboring white spruce). Side shade can cause crown asymmetry which strongly contributes to instability. Waldron (1995 in press) observed 16% reduction in the crown-radius of 12-20 cm DBH white spruce within rows where trees were 2.4 m apart and grown under an aspen canopy.

Severe side shade in pure coniferous stands, and probably in dense clumps of white spruce understory, can result in short crowns. In contrast, Norway spruce growing with hardwoods (that have greater crown transparency) is known to form larger and markedly better crowns, lending them higher resistance to wind damage than those in pure stands (Schütz 1990, Drescher 1965 cited in Schütz 1990).

a.   Crown Length

Trees with long crowns (reaching to the ground) are more resistant to wind damage than trees of similar height with short crowns. Long-crowned trees also have well-tapered stems. In addition to the lower center of gravity of long-crowned trees, their improved wind resistance may be the result of having grown in the open where they receive the benefits of both wind stimulation and greater

space for root development. Increased vigor resulting from abundant sunlight in open-grown conditions would also improve height-diameter ratio and thus wind stability. In fact, Oliver and Larson (1990) describe the "live crown ratio"—the ratio of crown length to tree height—as an index for tree vigor.

Crown length in conifers is closely and negatively correlated with "slenderness coefficient"—the ratio of height/DBH, i.e., slenderness coefficient decreases as crown length increases (e.g., Rottman 1986).

Because of this strong relationship, both crown length and slenderness coefficient are considered to be predominant tree characteristics governing wind stability. Live crown ratio (crown length/tree height) is sometimes preferred in the field for its easy visual assessment and interpretation. For fast estimates of the stability of Norway spruce stands in Central Europe, Remis et al. (1990) recommended the slenderness coefficients and corresponding values of live crown ratios summarized in Table 1.

Table 1:   Recommended slenderness coefficients and corresponding values of live crown ratios (live crown length/tree height).

Age Class	Height/DBH	Live crown ratio %
1-20	n/a	100
21-40	<80	75-100
41-60	<85	50-75
61-80	<90	50
80+	<90	full, uninterrupted canopy

A similar relationship, applicable to Norway spruce in Germany, is shown in Table 2.

Table 2:   Windbreak potential for Norway spruce in Germany related to slenderness coefficient and crown length percent.

	Potential for windbreak		
	low	medium	high
Slenderness coefficient	<80	80-100	>100
Crown length %	>50	30-50	<30

Because of these strong relationships, production of long-crowned trees through spacing and thinning treatments have long been advocated as a wind resistance measure in Norway spruce stands in Europe. Foresters early in the 20th century recommended that Norway spruce should have crowns to the ground until a tree is 25 years old (Bohdanecky 1926 cited in Rottmann 1986). A 40-year-old tree should have a crown length of 66% of tree height (Heger 1957). Kramer (1975, 1980) recommends that Norway spruce taller than 10 m should have a live crown of at least 50% of the tree's height for wind stability and that 60-70% gives even better stability.

Konopka (1977) showed significant differences in the live crown ratios of wind damaged (44-49%) and undamaged (78%) spruce trees and suggested optimal values of live crown ratio ranging from 52 to 73% depending on elevation zone or ecoregion. Spruce growing in mixed stands had about 8-14% higher live crown ratios than those growing in pure spruce stands (Konopka 1972 cited in Konopka 1977).

Other strategies aim to reduce crown size and thus reduce drag forces on a tree. This can be accomplished by changing from low density to higher density thinning regimes and maintaining a fully, closed canopy (Chroust 1980, Johann 1981, Slodicak 1993 in press).

The most promising approaches for estimating stand resistance to wind damage look at combinations of several tree characteristics. A simple model of the relative resistance to windbreak as a function of DBH and live crown ratio was developed for Norway spruce by Perina et al. (1968). The model shows that a tree with DBH of 13 cm can have a relative windbreak resistance of 40, 60, 80, or 100% depending on its live crown ratio, in this case 50, 62, 70, and 75% respectively (Figure 6). Note in particular that a value of 100 represents the highest resistance.

NOTE:
a value of 100
represents the
highest resistance
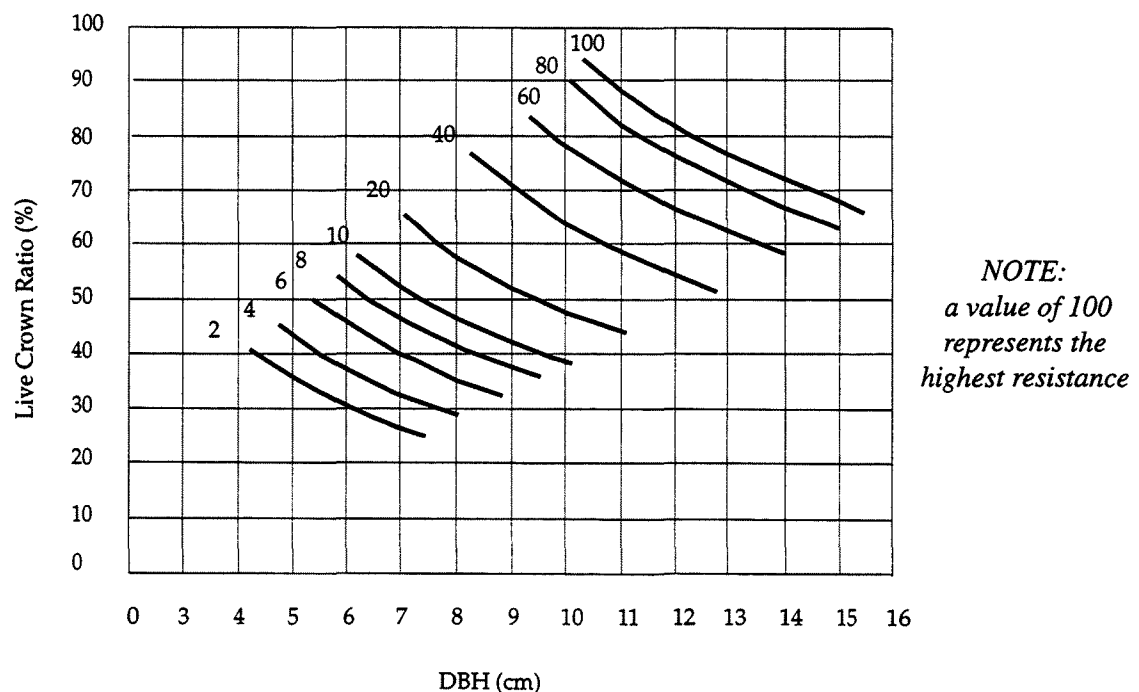
Figure 6.   Relative windbreak resistance of Norway spruce in relation to DBH and live crown ratio (after Perina et al. 1968).

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b.   *Crown Width*

Crown width is controlled by side shade (cast by neighboring trees) and by canopy closure. Both factors are directly related to spacing and stand density. Freely grown trees will reach a maximum crown width given unlimited growing space in both crown and root zones.

Crown width can also be influenced by ecotype. Mountain regions and sites that are wind- or snow-prone naturally harbor ecotypes with narrow or columnar-shaped crowns. Under the same conditions, trees with wider crowns are nearly always more vulnerable to windthrow.

Wider crowns add to the crown surface area and therefore increase wind pressure and drag forces on the tree. Narrow crowned spruces with a cross-sectional area of 19-24 m^2 were subjected to about half of the wind pressure exerted on wide-crowned spruce with a cross sectional area of 28 m^2 (Chroust 1980).

c.   *Crown Density*

Dense crowns increase drag forces and decrease wind stability. Branching habit and branch flexibility (ability of branches to bend with wind) are important to windfirmness and can vary between species and ecotype. Dense crowns can be easily damaged under heavy snow or ice loading conditions in combinations with wind. Heavy windthrow damage in lodgepole pine stands in Jasper National Park, Canada in 1990 resulted from such a combination of snow and wind loading.

The zone where dense branching occurs within the crown also influences tree stability. If the upper zone of the crown is more dense than the lower, the torque forces increase and wind stability decreases. Conversely, if the lower zone of the crown is dense, the resulting lower center of the gravity may increase wind stability.

Denser foliage resulting from fertilization increases wind and snow damage in coniferous stands. After a severe windstorm in southern Finland, the incidence of windthrow was twice as high on fertilized plots as compared with unfertilized plots (Laiho 1987).

Crowns become more dense after release. Intensified sunlight causes the number of buds to increase along with the number and size of needles (Oliver and Larson 1990). In terms of wind stability it is preferable that these increases occur in the lower zone of long-crowned trees. It follows then, that a stability rating for white spruce understory should consider crown density, in addition to live crown ratio. Both of these characteristics are strongly influenced by density and clumpiness of white spruce understory prior to and following aspen canopy removal.

3.   Slenderness Coefficient

Resistance to wind damage is significantly influenced by the form of stem. One of the most frequently used indices is the slenderness coefficient. The slenderness coefficient is a ratio of height to diameter (DBH) calculated in the same units, e.g., height 19 m: DBH 0.2 m = slenderness coefficient of 95. The inverse of slenderness coefficient is taper, expressed as the ratio of DBH to height, e.g., 1:95. Slenderness coeffecient may serve as an indicator of crown type, crown length, crown class, growth performance and root system size (Abetz 1979).

Many studies have shown that slenderness coefficient (or taper) is the principal factor affecting susceptibility to windbreak, snow damage and to some degree, windthrow (Brunig 1973, Faber 1975, Petty and Swain 1985, Abetz 1987, 1989, Slodicak 1987, Konopka 1977). The relationship of windthrow and slenderness coefficient is indirect. Lower slenderness coefficient can be an indicator of larger crowns, lower centre of gravity and a better developed root system (Chroust 1980, Slodicak, Personal Communication 1994).

In general, trees with a higher slenderness coefficient (low taper) are much more susceptible to damage than trees with low slenderness coefficient (high taper). When deciding on an acceptable range of height/DBH ratios, a combination of both wind risk and snow risk should be considered.

The desirable height/DBH ratios for adequate wind resistance vary according to species and country (Table 3). In the Netherlands, the maintenance of height/DBH ratio of no more than 50-60 is considered safe for Douglas-fir for average wind velocities (Faber 1975). In Germany, it is suggested that a ratio of about 80 is acceptable for Norway spruce (Abetz 1989). Evidence after the catastrophic storm in south-west Germany in 1990 showed that Norway spruce stands up to 20 m tall had good resistance against wind damage if the height/DBH ratio of the 400 largest trees in the stand did not exceed 80 (G. Kenk, Personal Communication 1993).

Table 3:   Critical slenderness coefficient values for different species and geographic locations.

	Instability Threshold	Extreme Instability	
Norway spruce	≥ 90	100-110	Europe
Norway spruce	>90		Germany
Norway spruce	≥ 80		Europe
Birch and oak	≥ 140	150-160	Europe
Beech (young stands)	180-220		Europe
Beech	≥ 140		Europe
Pinus radiata	≥ 60	≥ 100	Australia
Douglas-fir	> 50-60		Europe
Sitka spruce	> 60		N. Ireland

Data taken from: Konopka et al. (1987); Kodrik (1986); Kenk (Personal communication 1993); Abetz (1987); Cremer et al. (1982); Rottmann (1986); Faber (1975); Kramer (1980).

In Australian *Pinus radiata* plantations, Cremer et al. (1982) found that the height/DBH ratio for dominant trees was the most valuable index of risk of damage. Trees with a height/DBH value of less than 60 were stable while trees of all species with a value above about 100 were unstable.

In tree pulling experiments in Douglas-fir plantations the maximum turning moment of trees was

negatively correlated with slenderness coefficient, and positively correlated with stem volume and growing space (Kuiper 1986). In experiments with wind-induced tree motions, Mayer (1989) observed that the higher the values of slenderness coefficient of a Norway spruce tree, the lower its resistance to dynamic windloads.

Abetz (1987) documented a close relationship between the survival rate of crop trees and the slenderness coefficient 40 years after selective thinning a Norway spruce stand (Fig. 7). The stand was thinned when the potential crop trees were about 12 m tall. After 40 years, 100% of trees with slenderness coefficient of 60 or less at the time of thinning survived while the survival rate of the trees with slenderness coefficient of 100-110 was only about 10-15%. This may also represent a normal stand development pattern—dominant (crop) trees tend to have lower slenderness coeffecient, greater vitality and therefore, greater probability of survival (Slodicak 1987).

While, in this case, the survival-rate of Norway spruce trees after 40 years is correlated with their
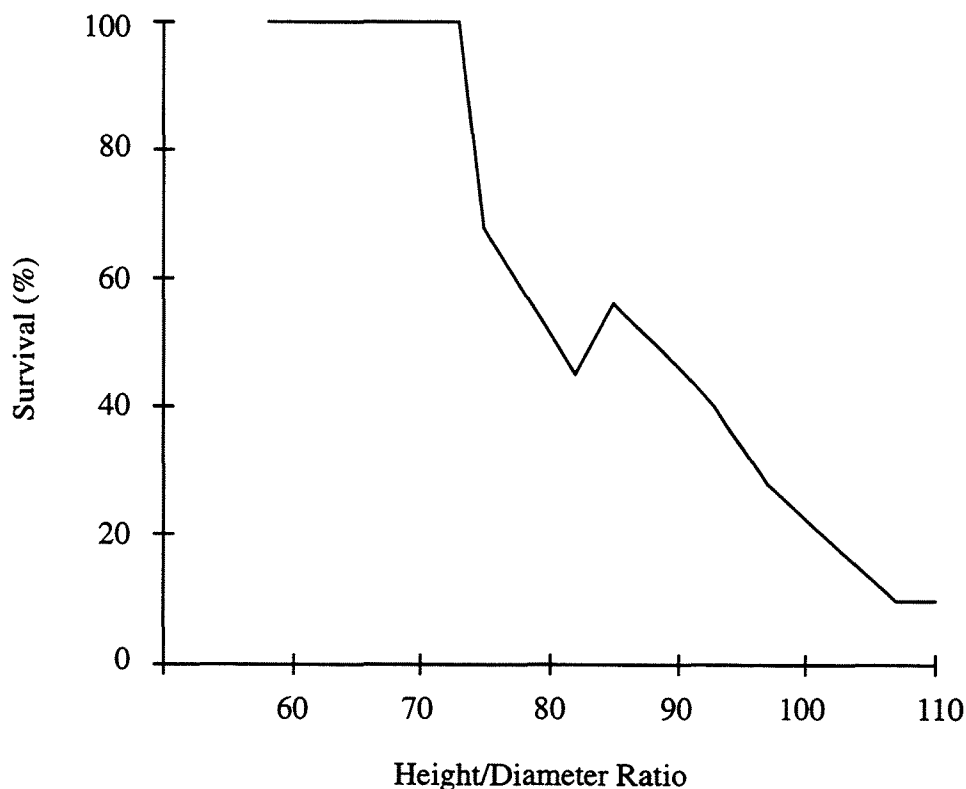
Figure 7.   The survival rate of Norway spruce trees 40 years after thinning correlated to their height/diameter ratio; cumulative mortality from snow and wind damage (after Abetz 1987).

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height-diameter ratio, the slenderness coefficient of Norway spruce is not always correlated with wind stability. There are situations where using other parameters such as crown length, or the top weight to root weight ratio may be more representative (C. Nielsen, Personal Communication 1990)[1].

Slenderness coefficient values tend to change with age. In softwood species, the values increase with age, culminate and then gradually decrease (Konopka et al. 1987). Knowing how stand density, and the corresponding slenderness coefficient values change over time, it may be possible to estimate or predict the critical period for stand stability.

The slenderness coefficient is also influenced by site productivity (site index) (Konopka 1977) and elevation (Slodicak 1985). On sites of better quality, slenderness coefficient is often high, indicating the stability of stands is low. The critical time period for stability in softwood stands—when the highest value of slenderness coefficient occurs—comes earlier on better site classes than on poorer ones.

It is evident that the threshold and critical values of slenderness coefficient vary with species, stand development, age and site. One must consider all these factors to assess stability. For example, two trees of similar height and diameter but with different crown size will have different centers of gravity and therefore different levels of windfirmness. Similarly, the relationship between height/DBH and tree stability can vary with crown class and may only apply to a certain crown classes. For example, in Norway spruce stands, the relationship held true for dominant trees, but was less applicable for suppressed trees in the same stand (Galinski 1989).

The most promising approaches for estimating tree stability are those which combine several parameters. Petty and Swain (1985) took such an approach, combining tree height, slenderness coefficient and wind speed for Sitka spruce. Figure 8 illustrates the wind speed needed to cause windbreak under various values of tree height and slenderness coefficient. In the example shown in Figure 8 the critical tree height for a wind speed of 25 ms^{-1} (90 km/hr) is about 15 m for a tree with slenderness coefficient of 100. This critical height changes to about 18 m for trees with a slenderness coefficient of 80.

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[1] C. Nielsen, Göttingen University, Göttingen, Germany
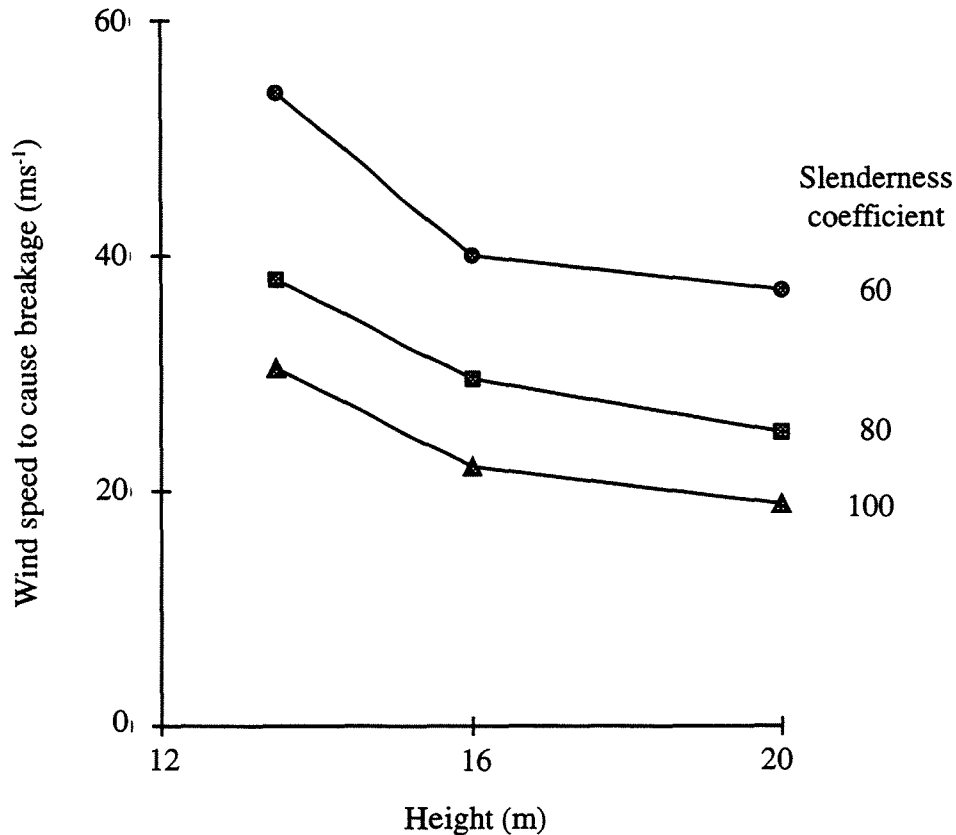
Figure 8.   Wind speed to cause windbreakfor Sitka spruce trees of three heights and three values of slenderness coefficient (height/DBH) (after Petty and Swain 1985).

At present, information on tree characteristics and critical wind levels is not available for Boreal forest tree species. It will need to be gathered by retrospective measurements in stands that have experienced wind damage. Preliminary data collected from white spruce exposed to wind after aspen canopy removal in Alberta show the differences in tree morphology between wind-damaged and undamaged trees. An example showing morphological characteristics of white spruce trees sampled in damaged vs undamaged stands, two years after aspen canopy removal, is provided in Table 4. The results indicate the potential for applying tree stability concepts in the development of a rating system specific to white spruce understory and two-stage silvicultural systems.

Table 4:   Comparison of tree morphology characteristics of damaged and undamaged white spruce understory trees 2 years after the removal of aspen canopy, Whitecourt area, Alberta.

	Leaning or Windthrown	Undamaged
	N = (28)	N = (21)
Height (m)	9.20	6.00 *
DBH (cm)	11.20	8.20 *
Height/DBH	81.00	75.00 *
Mean Crown Density[1]		
- lower	1.40	2.10 *
- mid	2.10	1.80 NS
- upper	2.80	2.10 *
Height to Crown (m)	2.50	1.60 *
Crown length (m)	6.70	4.40 *
Live crown ratio	0.80	0.88 *

[1]A higher number means denser crown

* significant at $P<0.05$

4.   Response to Release—Improvement of Tree Stability

When growing space and sunlight become available as a result of thinning or release from competition, a tree responds by expanding its crown and roots. How rapidly release growth occurs depends on the tree's condition at the time of release (Oliver and Larson 1990). The most critical factors in this process are the crown size and crown condition.

After thinning or release there is a temporary destabilization of individual trees and the stand as a whole. Following this, stability progressively improves. The speed of this process is dependent on the rate of growth and subsequent changes in tree morphology, and also on the changes to stand density and site conditions.

When trees are removed from a dense stand (one which had reached crown closure), remaining trees that are extremely thin relative to their height (high slenderness coefficient) may fall over due to the loss of support from adjacent trees (Groome 1988). Trees with a very high slenderness coefficient are also unable to further develop their small crowns. For example, Norway spruce with a slenderness coefficient of 100 or more showed little to no improvement in crown morphology after thinning (Abetz 1987). Therefore, thinning should emphasize the negative selection from below that mainly removes thin trees with high slenderness coefficient.

Young trees which have developed at wide spacing respond quickly to released conditions. As such, the time required to improve stability can be shorter if stands are planted at wider spacing or

if thinning or release treatments are applied very early. With Norway spruce, it is recommended that stands be treated before the culmination of periodic height increment. Under conditions of mid-elevation sites in the Czech Republic, Chroust (1980) recommends that treatments should take place before the spruce reach a height of 7 m, and for windthrow resistance, heavy thinning should cease in spruce stands at the age of 20-40 years (Slodicak 1987).

Pine species, for example Scots pine, may respond more slowly to treatments than spruce species, owing to greater crown transparency and earlier growth culmination.

Changes most important for improving tree stability following release are: diameter growth, crown extension, and root system strengthening. After a successful treatment, increased diameter growth should occur not only in the basal part of the stem but also in the critical profiles of the stem where snow and wind breakage most frequently occur.

The extension of the crown may have even greater importance in tree stability than diameter growth. The crown extension of Norway spruce from 1/3 to 2/3 of tree height increased stability by over 100% because of the lower center of gravity (Chroust 1968).

When growing space increases, crowns and root systems may grow at different rates on different sites. Kodrik (1983) measured the response of thinned silver fir and Norway spruce and found, on nutrient-rich sites, that the crowns expanded in radius more than the root system. In contrast, on nutrient-poor soils, the radius of the root system enlarged more than that of the crown.

a. Wind stimulus

Root system strengthening is stimulated by wind. The tree must be given sufficient stimulus to produce strengthening wood tissues and propping roots on the lee side of the tree. Trees grown in closed, fully-stocked stands or under a protective canopy have received very little stimulation and are less adapted to wind. When the stand is thinned or the canopy is removed through silvicultural treatments, wind stimulus gradually strengthens the roots and the root system expands.

Root growth is highly sensitive to soil aeration. Saturated soil conditions (which may or may not be related to silvicultural treatment) can prevent the development of the root system and negate stability improvement expected after the treatment.

b. Stability period

In coniferous stands older than 30 years, the five-year period immediately following treatment is most critical to stability improvement, and hence, reduction in the probability of windthrow.

Lohmander and Helles (1987) predicted the probability of windthrow in spruce (*Picea abies* and *Picea sitchensis*) stands as a function of the time since the most recent thinning. They found a very rapid decline in windthrow probability in the years 1-3, a slight decline between years 4 and 5 and a very slight decline or no change between years 5 and 10 (Figure 9).

20
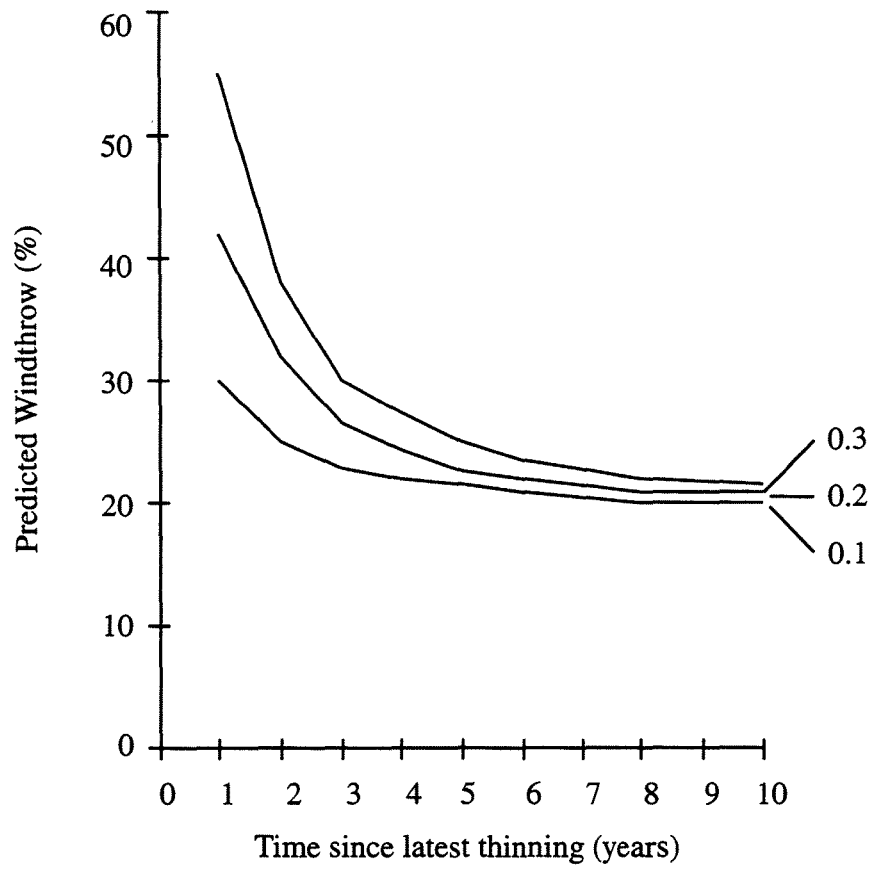
Figure 9.   Predicted probability of windthrow in spruce stands as a function of time since the latest thinning and thinning intensity (thinning volume/stand volume) (after Lohmander and Helles 1987).

In thinned stands of *Pinus radiata*, the incidence of windthrow was 88% in stands thinned in recent months compared with 38% in stands thinned more than 5 years prior (Cremer et al. 1977) (Figure 10).
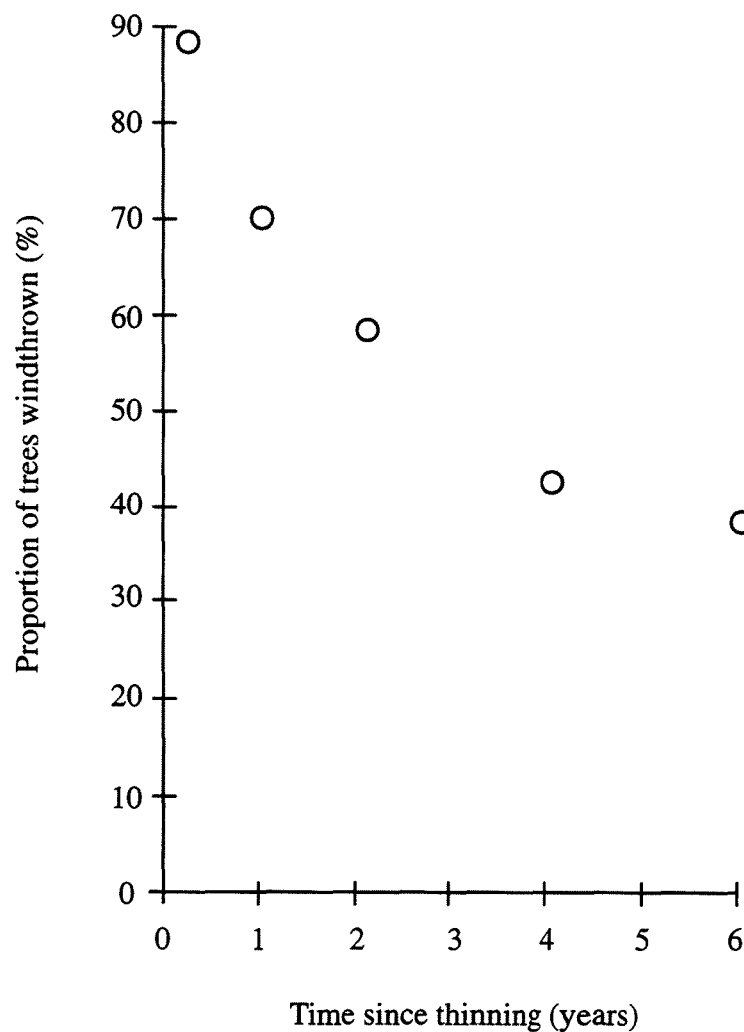
Figure 10.   Windthrow after thinning in stands of *Pinus radiata* located downwind from a clearcut area (after Cremer et al. 1977).

In southwest Sweden, Persson (1975) related the incidence of wind damage to tree height and years since last thinning. For three stands where the time since thinning differed, the incidence of damage increased exponentially with tree height (Figure 11).
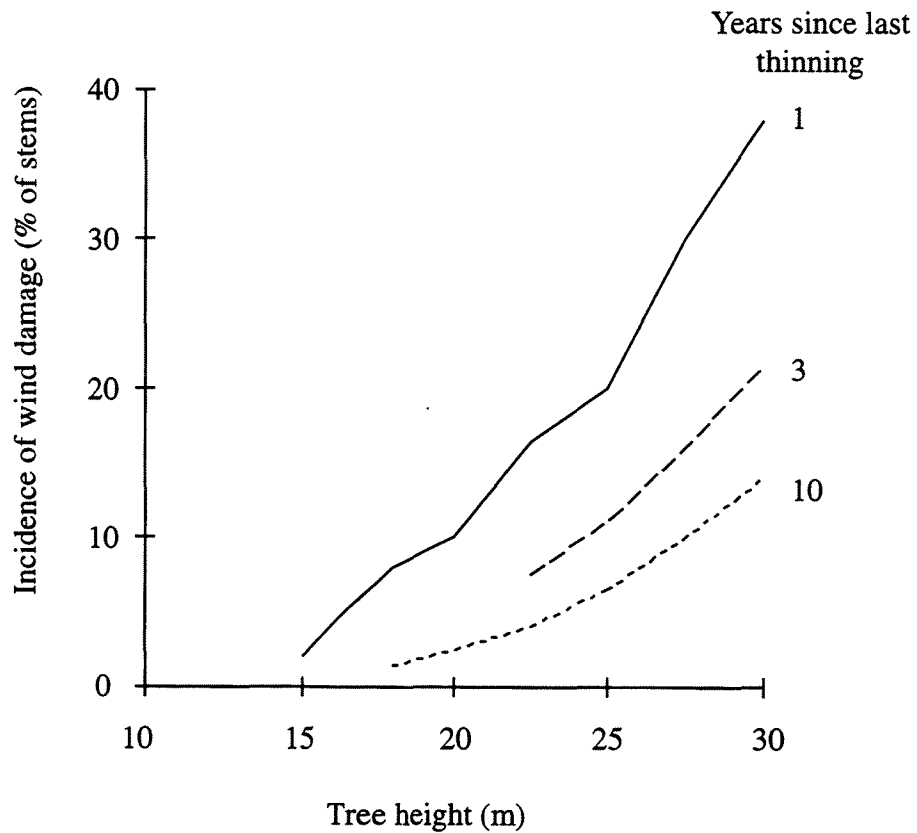
Figure 11.   Effect of tree height on wind damage 1, 3 and 10 years after last thinning (After Persson 1975).

In southern Finland, in a large-scale assessment of windthrow in Scots pine and Norway spruce stands, the damage was frequent in stands where four years had elapsed since last thinning. The damage was highest in plots which had recently been thinned and fertilized—being almost six times greater than that in unfertilized plots which had not been thinned for a long period (Laiho 1987).

In Alberta, in white spruce understory released after the removal of aspen overstory, there was negligible windthrow between three and five years after harvesting, while in the first three years, windthrow losses ranged 5-25% in different height classes. In the same stands the values of slenderness coefficient of released white spruce increased significantly over 5 years since harvesting aspen canopy (see Section H.2.4 and Navratil et al. 1994).

F.   STAND STABILITY

1.   Stand Structure and Stand Edges

Windthrow in a forest stand is related not only to the individual stability of a tree, but also to the degree and extent of interruptions in the forest canopy. Wind flows steadily over the canopy of even-height, fully-stocked forests. However, wind becomes turbulent when it penetrates openings or when the flow is broken by an abrupt increase in stand height (5 m or more).

In both young and old stands that have not developed wind resistance, sudden exposure of stand edges causes a consistent pattern of damage. Wind damage in unprotected edges creates funnel-type openings through which damage spreads and penetrates into stands. Such damage can be severe and extend hundreds of meters downwind in large swaths (Somerville 1980). The exposed edges may result from: harvest on a stand's windward side; a break or strip in the stand wider than 40 m (Somerville 1980); or any large gap created by natural or man-made disturbance. The exposed edges gradually stabilize over about 15 years (Busby 1966), depending on stand age and stand density, as trees develop wind-resistant characteristics.

Since much of a stand's stability is dependent on well-established and well-protected stand edges, edges need to be stabilized and wind damage to them should be prevented. In intensively managed forests of Europe, elaborate systems of severance cuts and lines that are designed to produce stabilized, windfirm edges are rigorously embodied in long-term harvesting and silviculture plans. Similarly, in extensively managed forests, older roads and seismic lines can be utilized for the same purpose. Risk of windthrow can also be reduced by designing the edge so it is protected by the landscape rather than creating an edge perpendicular to the wind direction (Oliver and Larson 1990).

Models of wind movement show that there is a dammed zone or air pillow in front of the forest edge. Wind moves up, over, and also through the edge with eddies falling in behind the edge. Commonly, damage is highest a short distance into the stand, while the trees directly on the edge remain standing. At a distance of several tree heights into the stand, the wind forces decrease and stabilize (Fraser 1964, Raynor 1971). Windthrow sometimes occurs in zones more distant from the windward edge, from a few tree heights to about 10 heights. An example of damage within a stand in relation to the distance from the exposed edges is presented in Figure 12.

Relative damage shown in Figure 12 is calculated as the ratio of % damage in each 100 m strip to the mean % damage in the first 500 m from the stand edge. Data is for 25 year old stands of *Pinus radiata* with open ground to windward (After Somerville 1980).
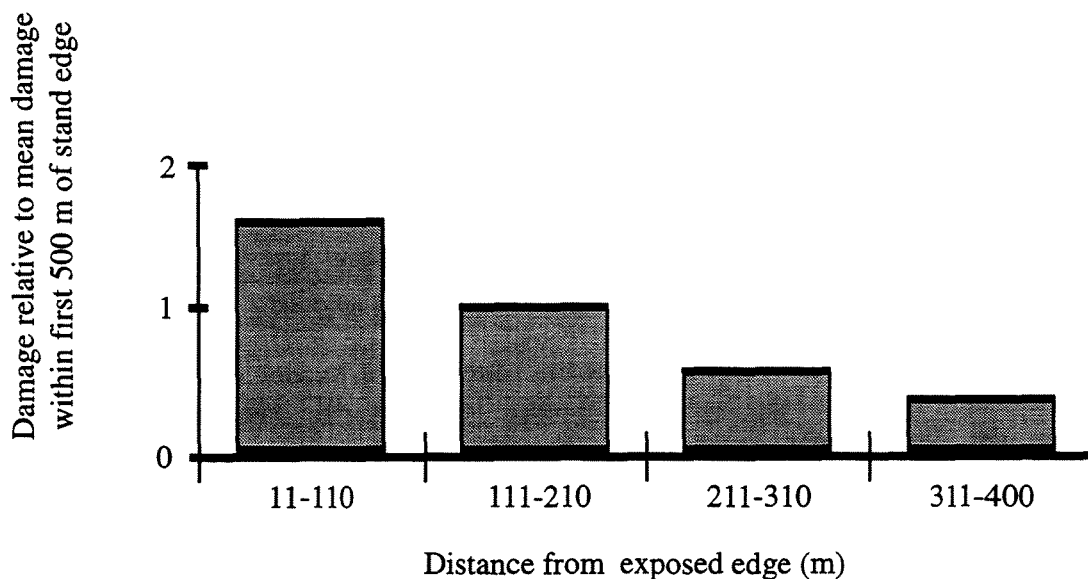
Figure 12.   Distribution of wind damage in 100 m wide strips in relation to exposed edges.
(After Somerville 1980).

Relative damage is calculated as the ratio of: % damage in 100 m strips to mean % damage in the first 500 m from the windward edge of the stand. These are 25-year-old stands of *Pinus radiata*.

The extent of wind damage can be reduced by influencing the permeability or structure of stands on the windward side of the stand edge. To prevent damage, a wide, stable wind belt is recommended. Kramer (1980) recommended a wind belt be 30-50 m wide to adequately protect the stand. The wind belt should be established early in stand development and its density should be low on the edge and gradually increase toward the stand. Trees grown at wider spacing develop a stronger root system and better wind stability, and thus an ability to resist the wind turbulence generated by edge trees (Figure 3, a & b).

It is important for edge trees to be exceptionally stable and have low slenderness coefficients. Kramer (1980) determined the width of strips between adjacent stands necessary for Norway spruce to develop the required height/DBH ratio. According to his results, the spacing between two stands should be 10-13 m to obtain stable border trees with height/DBH values of 70-80 (Figure 13).

$$y = 102.64 - 2.63 x$$
$$r = 0.682$$
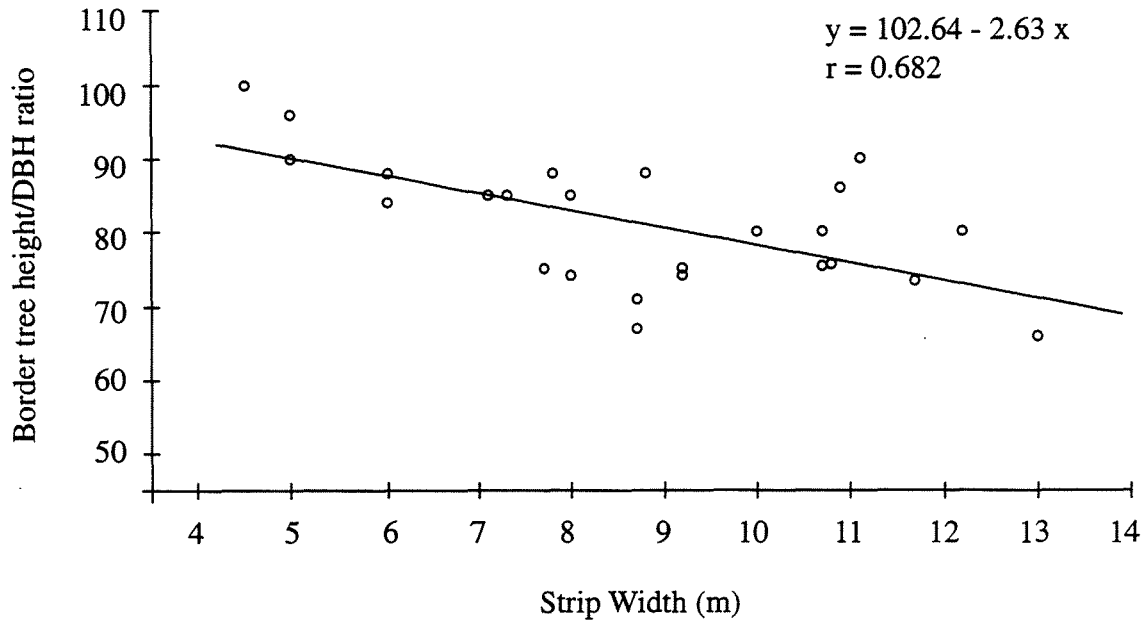
Figure 13.   Mean height/DBH ratio of 50 year-old Norway spruce border trees in relation to strip width (After Kramer 1980).

Mixed-species with irregular edges are the most stable and most efficient in breaking air flow. The dominant trees of the belt should be conifers as they reduce wind force better than broad-leaf trees and function well after leaf fall. To secure stability in exposed Norway spruce stands the following species have proved capable of forming stable edges on poor sandy soils: oaks, Japanese larch, Scots pine, Austrian pine, Sitka spruce and white spruce.

It is often recommended that permanent stand edges should be treated in a manner similar to shelterbelts in agriculture in order to create a degree of permeability (Figure 3, c). Deciduous species may be used for this purpose. Alternatively, high pruning of coniferous species can increase permeability (Savill 1983, Matthews 1989, Rottmann 1986).

The windward edge of a stand should have as few indentations as possible. Wind damage can be frequently attributed to recognizable turbulence starting points such as road turns, borrow pits and well clearings. Indentations in the edge of a stand, especially V-shaped or egg-shaped openings, produce a funneling effect which increases wind speed (Curtis 1943 quoted in Gratkowki 1956). Damaging winds may come from any direction, therefore, stands should have all edges stabilized.

The intensity of wind damage in Norway spruce stands with heights over 25 m, was influenced by stand size. Smaller size stands up to 5 ha had clearly less damage than 5-10 ha stands and stands above 10 ha (Vicena et al. 1979).

## 2.	Species Composition

Species composition, if it can be manipulated, will help ensure stand stability. The extent of wind damage can be greatly reduced by creating a proportionate mixture of wind-prone and wind-resistant species.

Differences in wind resistance between species can be partially attributed to branch flexibility and crown permeability. While spruce and pine create high drag with their stiff, resistant branches and foliage, Douglas-fir and western hemlock branches are flexible and stream out in the wind (Savill 1983).

The greatest influence is gained by having a mixture of shallow-rooted and deep-rooted species. Bazzigher and Schmidt (1969) indicate that deep-rooted or heart-rooted species such as Scots pine, lodgepole pine, and beech are more stable than shallow-rooted species, notably Norway spruce. However, Lohmander and Helles (1987) found that Norway spruce was more windfirm than silver fir and Douglas-fir in Sweden. Japanese and European larches are known to be wind stable and were used to create stabilizing zones in Norway spruce plantations (Nickelmann 1981 quoted in Savill 1983).

In wind damaged pine plantations in southeastern Ontario, white pine was the most windfirm species, while jack pine was the most heavily damaged species, followed by Scots pine and red pine. White spruce also suffered heavy damage (Stroempl 1971).

Soil, site and stand history differences may confound or influence locally observed windfirmness ratings. In fact, there are indications that many tree species are rather windfirm, provided that they have been grown under wind exposure and in suitable densities.

Hardwood species have, in general, the advantage of being deep-rooted. In addition, some of them can tolerate water-saturated soils. Considering this, the use of hardwoods may be an attractive option where wind storms are common during the leafless period. In central Europe, windfirm hardwoods have been introduced into forests which were predominantly Norway spruce. This change was partially provoked by large wind damage losses in the past several decades. The spatial distribution of hardwoods introduced into coniferous stands must be considered. Pockets of high turbulence were observed in spruce stands with introduced alder and birch in Great Britain (Savill 1983).

The most endangered are stands with more than 60% of spruce (Norway spruce). Beech in natural mixtures with spruce increases resistance to wind and snow, while in spruce–fir stands it is sufficient to have only 10% of beech to make the stand resistant, in pure spruce stands this addition should be at least 40% (Perina et al. 1968). The beech should be not only properly distributed, but also included in the upper canopy layer.

An approximate wind resistance rating of stands with different composition applicable in Eastern Europe was summarized as follows (Badea 1964 cited in Perina et al. 1968):

1.	Resistant stands that can withstand winds up to 104 km/hour (29 m/sec.): mixed stands of deep rooted species with well developed stems and crowns such as oak–beech and fir–beech–spruce stands.

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2.   Sufficiently resistant stands that can withstand wind speeds up to 82 km/hour (23 m/sec.): monocultures of oak, beech, fir; can contain small addition of other species.

Multi-storied stands have an advantage over single-story stands. In multi-storied stands, wind speed is reduced by 10-40% as compared to single-storied stands (Wolfe 1939 quoted in Dolezal 1956).

3.   Stand Density and Density Management

Wind stability of a forest stand can be influenced by two opposite density management strategies.

The first strategy aims at reducing the roughness of the canopy and maximizing neighbor support inside stands. This is achieved by maintaining high density, homogenous, even-aged stands. The level of wood production may be high, but the vulnerability to disturbance factors remains high and requires a strict adherence to density management regimes.

Initial spacing and thinning regimes required to achieve and maintain desirable stand stability through this approach in European spruce stands have been intensively studied and are described in the European silviculture texts (e.g., Burschel and Huss 1987, Kramer 1984).

The second strategy strives for better wind resistance of trees forming a stand, based on improving stability characteristics of roots, crown and stems. Management practises to improve this stability are very flexible; the stand may be heterogeneous and may contain many species. Wood production may be lower, but the vulnerability to wind and snow damage is also lower (e.g., Faber 1975).

The second strategy based is gaining more use in the management of coniferous forests in Europe. It is believed that favorable slenderness coefficient and crown length plus wind stability can only be achieved through the establishment of low density stands or early, repeated pre-commercial thinnings. Remedial treatments to re-establish low values of slenderness coefficient, after neglected care in early density management, have limited success.

Wider spacing is a prerequisite for the development of well-crowned, well-tapered and well-rooted trees which bend in the wind rather than break or become uprooted. The large crown size and correspondingly large drag force on trees growing at wide spacings are apparently more than compensated for by the stronger stem and roots (Blackburn et al. 1988, Oliver and Larson 1990).

Silviculturists working in areas subjected to damaging winds, increasingly advocate lower densities at stand establishment followed by no thinning or by limited timely thinnings. In Europe the recommended planting levels are reduced from a traditional planting density of 10,000 trees/ha to 2,500 trees/ha. In special treatments for crop trees, 1000 trees/ha has been targeted (Abetz 1987, 1990, personal communication). In New Zealand a wider spacing means reducing from 1000 trees/ha down to fewer than 200 trees/ha.

The number of thinning treatments should be kept to a minimum, since in the first five years after thinning, stands are more vulnerable to wind damage. This is partly due to enhanced wind penetration into the canopy after thinning, initiating turbulent wind patterns. Increased temporary windthrow vulnerability will eventually be countered by changes in the slenderness coefficient and other tree attributes that tend to improve their resistance (Miller 1986).

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Type and spatial arrangement of thinning may affect wind penetration into a stand. Line and row thinning has been found to increase wind and snow damage compared to selective low thinning (Eriksson 1986).

An example of the interaction between stand density, height and slenderness coefficient and the maintenance of a desirable slenderness coefficient, in relation to height by manipulating density, is shown in Figure 14 from Rottman (1986). He interprets a slenderness coefficient value greater than 90 as a sign of poor stability. Stands with a slenderness coefficient of less than 90 should have a density less than 1300 trees/ha for tree height 10 m and less than 700 trees/ha for tree height 20 m.

The prevailing strategy for preventative action against snow and wind damage in Norway spruce stands in Europe is gradual thinning. Individual tree stability is built in young stands through wide spacing or heavy early thinning. At a later stage, a closed canopy is maintained by keeping thinning intensity low. The resulting stands are characterized by mutual shelter of individually stable trees (Slodicak 1993).
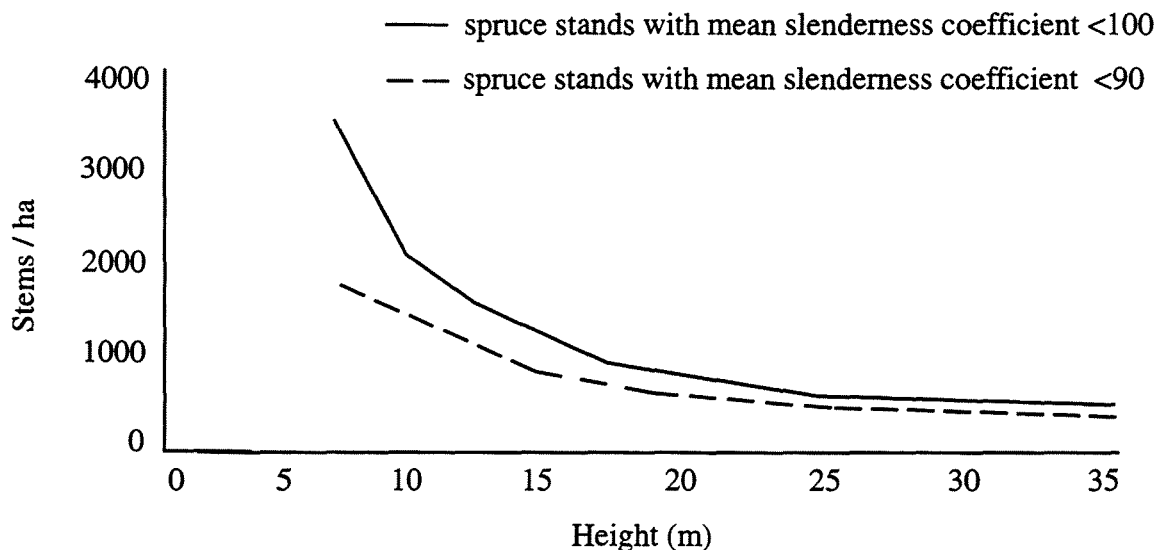
Figure 14.   Slenderness coefficient in relation to height and stand density. Norway spruce, Germany (Rottman 1986).

G. EXTERNAL STABILITY

1. Sheltering Effects

Wind flow over forested terrain is modified by the sheltering and diverting effects of both topography and forest stand structure. A terrain or stand feature which blocks the wind is said to have a *sheltering* effect, while a terrain or stand feature which changes the direction of the wind is said to have a *diverting* effect. The angle of inclination from the base to the crest of the feature is the key influencing factor for sheltering.

Mathematical models for estimating surface winds over specific terrain-types have been developed for fire protection purposes (e.g., Ryan 1983, Pickford 1990) but have not been adapted for predicting risk of wind damage in forest stands.

a. *Sheltering effects of upwind stands*

Sheltering effects of stands located upwind from stands requiring protection (i.e., shelterwood strips or released white spruce understories in open cutblocks) are well-recognized and usually incorporated into silvicultural and harvest plans.

Most meteorological studies of wind behavior within various stand types concentrate on wind penetration into the forest edge and wind behavior within the stand. Very little information is available on the speed change of winds leaving forest stands and entering open cutblocks—knowledge that would be particularly helpful for minimizing windthrow in retained white spruce understory. McNaughton's (1989) review paper on micrometeorology of shelterbelts and forest edges concluded that little information is available on sheltering effects on the lee side of forest edges.

We do know that when winds meet the forest edge the wind speed decreases slowly as the edge is approached, and moreso beyond the edge at both the above-canopy and below-canopy levels. At some height above the canopy the speeds are equal to those over open terrain.

Zentgraf (1952) and Raynor (1971) found that deciduous forests slowed within-the-stand winds to 23-50% of upwind, open-field speeds. The amount of decrease was dependent on edge density, forest type and external wind speed. Coniferous stands, on the other hand, reduced wind speed to 10-30% of upwind, open-field speeds (Nägeli 1954, Percin 1960). These decreased speeds reach an equilibrium within the stand at a distance of 10-20 times the forest height (Nägeli 1954, Meroney 1968).

When winds leave the forest stand and enter an open area, wind speeds increase. This is critical information for designing protective shelter stands for retained white spruce understories.

Raynor (1971) measured wind speeds into and out of a closed canopy stand of red and white pine (mean height 10.5 m) and compared them to the overall upper wind speed measured at 46 m. He found that the wind speed just above the canopy (14 m) was 48% of the 46 m measurement. In the downwind clearing, 30 m past the sheltering stand, windspeed increased to 64%. Wind speed at crown level (7 m) increased from 10% within the stand to 45% in the clearing.

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Using the functions developed by Raynor (1971), wind speeds can be approximated for both a sheltering stand and an adjacent clearing. If the wind 46 m above the ground is measured at 90 km/h the corresponding stand and clearing wind speeds may be estimated as in Table 5.

Table 5: Estimated wind speeds in clearings and sheltering stands for a 90 km/hr wind.

	Within a sheltering stand		30 m distance into the clearing	
Height	7 m	14 m	7 m	14 m
Wind speed	9.0 km/h	43.2 km/h	40.5 km/h	57.6 km/h

If we use a 55 km/hr wind as the threshold for windthrow damage in unstable trees, a sheltering stand of 10 m pine provides effective protection against a 90 km/hr wind for trees up to about 14 m height in a 30 m wide band adjacent to the edge of the sheltering stand.

Similar information was presented by Vicena et al. (1979) (Figure 15). The diagram shows that wind speed within the stand is reduced to about 2% of the original speed at 210 m from the windward edge of the stand. When a wind leaves the stand it accelerates to about 30%; at 50 m into the clearing it reaches 80%; and at 100 m it returns to 100% of the original speed (Vicena et al. 1979). No information was given on the stand characteristics or wind speed level.
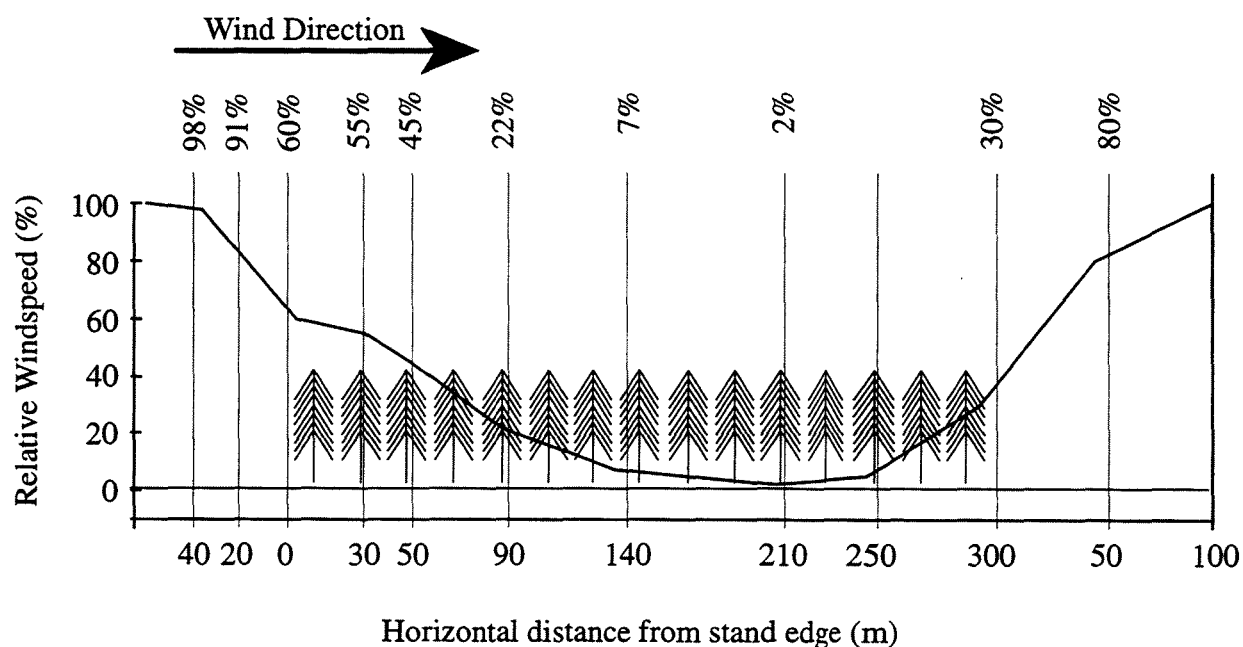
Figure 15. Relative wind speed in a forest stand and adjacent open areas. (After Vicena et al. 1979.)

For a moderate wind speed of 22 km/hr, Nägeli (1954) found that wind reaches about 75% of its original speed at approximately 200 m from the lee-side stand edge. The sheltering stand was a 70-80 year-old, 28 m high, conifer complex (Figure 16).
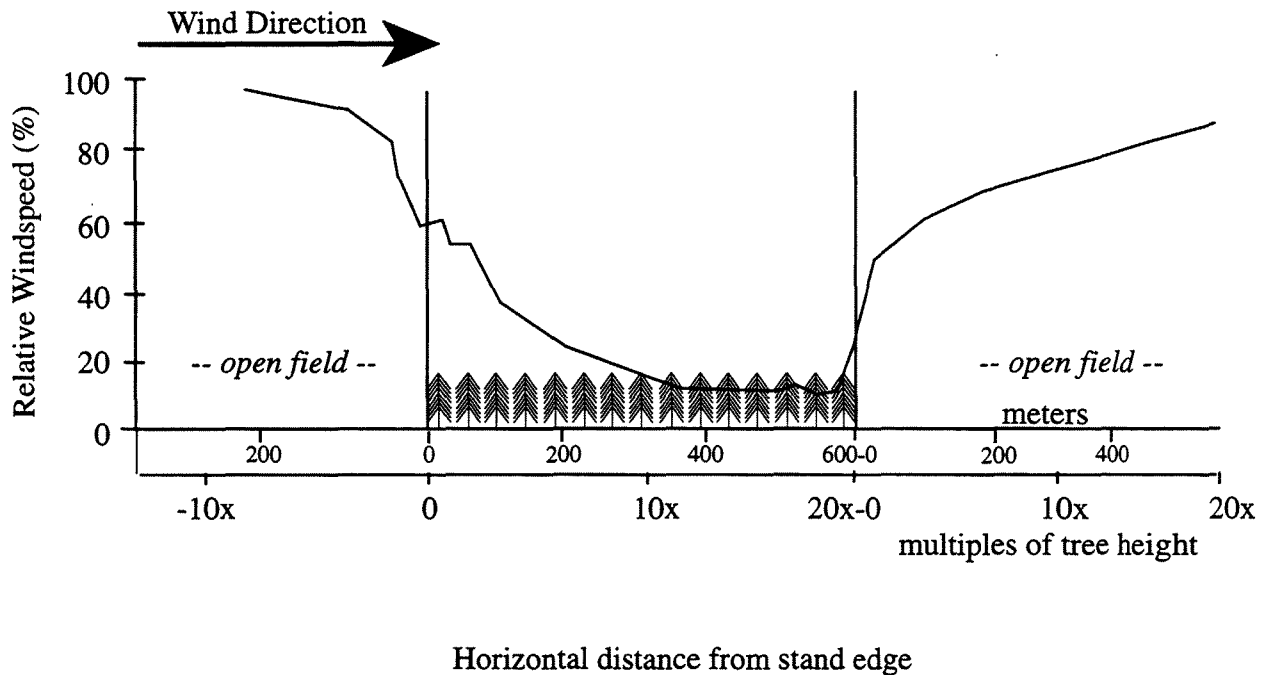
Figure 16. Relative wind speed in conifer stand and adjacent open fields (After Nägeli 1954).

The relationships presented here are from older literature sources, and may need to be refined as new information becomes available from wind behavior studies in progress (A. Black, University of British Columbia; J. Wilson, T. Flesch, Department of Geography, University of Alberta). It should also be recognized that different wind speeds and roughnesses of the forest stand can affect the extent of turbulence and width of the zone of protection, making interpolation from one site to another difficult.

2.   Topography

Risk of wind damage is decidedly influenced by topography—resulting in either an increase or decrease to wind speed and wind force. In hills and mountains, the changes in wind speed and wind force occur as lee-slope turbulence, valley funneling, assailing winds and along-slope and elevation acceleration. The wind speed changes and turbulences associated with topographic effects are complex. In general, wind chooses the path of least resistance and wind speeds change most where a stream of wind is forced to take a change in direction.

In mountainous regions, wind damage in forest stands most frequently occurs in valleys and mountain saddles. This relationship has been documented both in Europe (e.g., Vicena et al. 1979, Hütte 1968) and North America (e.g., Alexander 1967, 1975, Gratkowski 1956).

Valleys that are parallel to the wind direction are especially prone to become "wind-streets." Funneling of a wind up a valley results in increased force on the sides and at the head of a valley (Weidmann 1920, Alexander 1975). Wind can even follow valleys that change directions as much as 90 degrees. Highest damage to forest stands occurs where valleys narrow or change directions. Heavy damage may also occur in and beyond the gaps and saddles of main ridges (Ruth and Yoder 1953).

Winds tend to follow the ground contours where slopes are gentle. Gloyne (1968) suggested approximate limits for these slopes: windward slopes 20-25 degrees and lee slopes 5-10 degrees. In terrains with slopes 5-8 degrees, wind closely followed the terrain without a recognizable difference between the windward and leeward sides, whereas with slopes of more than 10 degrees the difference was distinct.

Low and gentle hills and ridges are, for the most part, bypassed by striking air-masses. Even strong winds are able to follow gentle and moderately sloping grounds, facing either into or away from the wind, without producing damaging effects. Wind speed lessens somewhat before and after the hills but it increases on the peaks. In these situations the damage is more on the peaks or mountain plateaus than on slopes (Rottmann 1986).

On the leeward sides of hills, a sheltered, relatively calm zone frequently develops, but not always. James and Dier (1968) explained that windthrow damage on the leeward slopes of moderately sloping ground was caused by violent eddies created by a bluff slope on the side away from the wind.

If the hill is narrow and convex, the downward-rolling eddies may combine with swirls coming around the hill and rotate horizontally around a vertical axis thus producing powerful turbulence (Rottmann 1986). Depending on hill size, there may be a wind-calm zone on the bottom of the windward side.

In larger and steeper mountains and in hills with long windward slopes, wind speed increases with increasing slope. Data from damage assessments in Europe document that the extent of damage is twice as high in mid- and upper slopes than in lower slope positions. Similarly, the greatest amount of damage was observed on the windward upper slopes of mountains and on mountain tops in the Pacific Northwest (Alexander 1967, 1975).
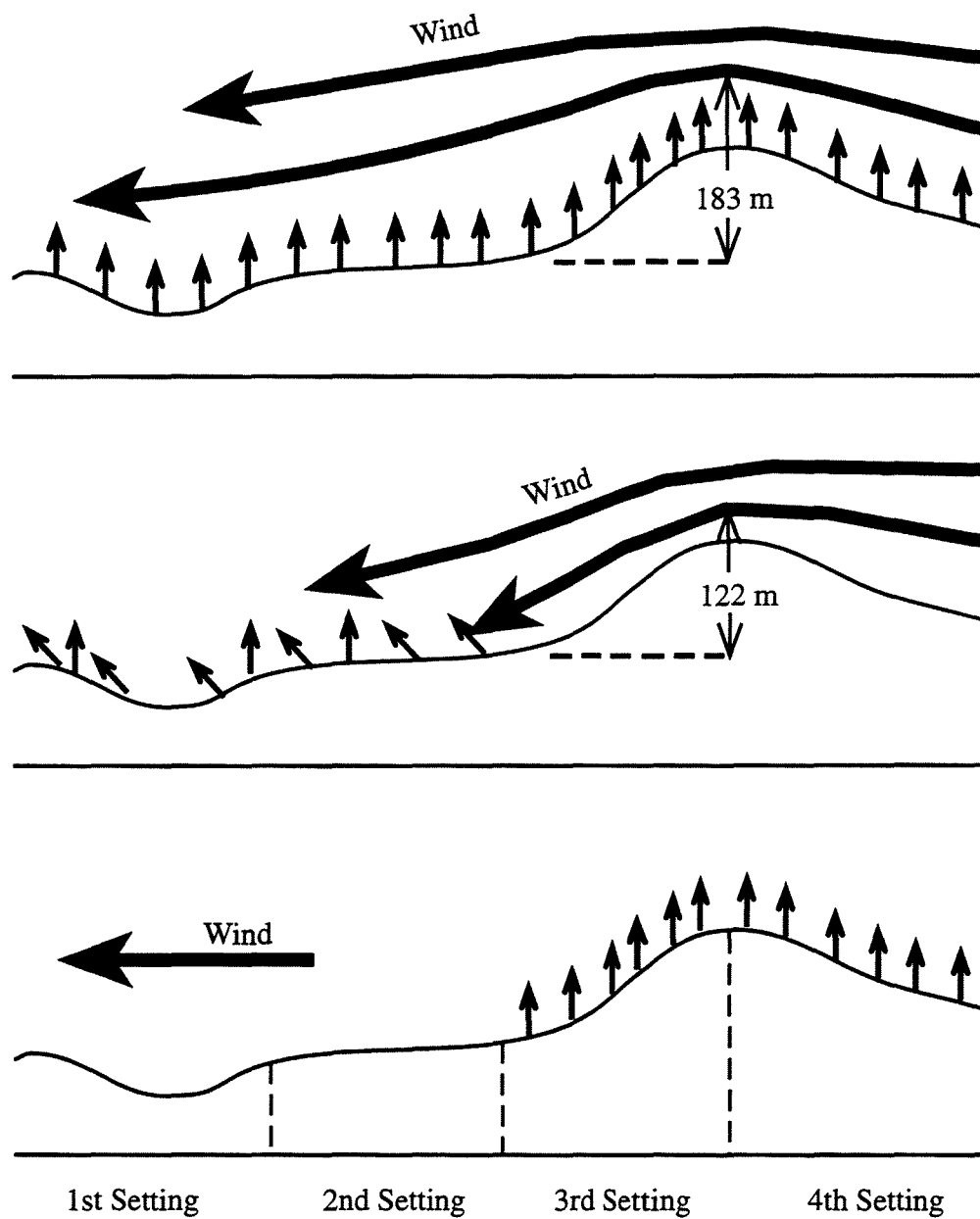
Figure 17. Windthrow damage after removal of the protective stand on the ridge: old growth Douglas fir stands in Oregon (1956).

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Susceptibility of forests to damage is greatest where both turbulence and wind speed are increased (Hütte 1968). This occurs where air currents are pushed upward by steep mountains and they meet moving air masses. The consequence, is that both the wind speed and turbulence increase. On the leeward side of the mountain, a wind-calm zone up to several hundred meters wide can develop before wind, pushed firstly to upper strata, again starts following the contours of the land. This wind-protected zone is usually associated with *assailing winds* that strike the ground at the end of the calm zone and cause high damage (e.g., Heger 1957).

Even in an area with considerable topographic features, soil factors may dominate the windthrow problems. Wangler (1976) analyzed the 1967 wind storm damage in Baden Württemberg region of Germany and found the highest damage occurred on flat terrain, with minimal damage on the surrounding slopes. Flat lowlands are often characterized by wet and poorly-drained soils, which could have been a contributing cause.

The influence of topography can also be positive where it creates a sheltering effect for trees on adjacent higher ground. Topography can be particularly important in reducing local wind speeds. A low elevation site with no adjacent high ground may be associated with high wind exposure (Miller 1985). A simple characterization of the topographic shelter of a site can be obtained by using "topex" values. The topex value is a numerical value obtained by the summation of eight skyline angles taken at the cardinal compass directions. The topex system has been found to be a useful relative indicator of site exposure and is employed in wind hazard rating in the United Kingdom and Ireland (Miller 1985, MacKenzie 1976).

3.   Silviculture and Topography

Silvicultural treatments for increasing wind resistance of stands should be intensified on the windward slopes where wind penetrates more easily into and under the stand canopy. On windward slopes, clearcut strips should not be located with the longitudinal axis parallel to wind direction, since they tend to funnel wind to downwind stands. In all situations where topographic features enhance wind speed, strips or cutblocks should not be parallel to the prevailing wind direction.

The combined sheltering effect of topography and stand can be negated by poor selection of silvicultural system and poor sequencing of harvest. In the example in Figure 17, the removal of a protective stand on the ridge by clearcutting: reduced the protective height of the ridge; exposed the stand on the lee side of the ridge to forceful winds; and caused a large area of windthrow (Gratkowski 1956). Windthrow in this situation can be minimized by sequencing cuttings "into the wind" as shown in the lower diagram of Figure 17.

4.   Site and soil effects

The incidence of windthrow in conifers is related to the effectiveness of root anchorage. Poor root anchorage and resultant susceptibility to windthrow is frequently attributed to a shallow, weak or inadequately (i.e., asymmetrical) developed root system. The development and wind stability attributes of the root system are in turn influenced by soil conditions, as well as stand conditions (stand density, species composition, age). In general, on deep, well-drained soils and in low density,

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multi-species stands, trees are said to have a better developed root system than in shallow or poorly drained soils and even-aged, dense monocultures.

The following components of root anchorage as characterized by Coutts (1983) emphasize the important interaction of both root morphology and soil physics:

a.   the dimension and mass of the root-soil plate

b.   tensile strength of roots and soil beneath the plate

c.   root and soil tensile strength and root/soil resistance on the windward perimeter

d.   the stiffness of the hinge of large roots on the lee side

Root morphology, mainly the depth and size of structural roots, is modified in different soil environments largely in response to soil aeration and soil penetrability. Depth of roots (or shallowness of root systems) is frequently used in quantifying wind risk. The British windthrow hazard classification uses three broad soil groups based on rooting depth (Table 6) (Miller 1985).

Table 6.   Soil scores based on root development and broad soil groups.

Root development	Soil group	Score	
Unrestricted rooting in excess of 45 cm	Brown earths, podzols, intergrades to ironpan	0	(very low risk)
Restricted rooting but some structural root penetration in excess of 25 cm	Deep peats, loamy gleys	5	
Very restricted rooting under 25 cm deep	Peaty gleys, surface water gleys, waterlogged soils	10	(very high risk)

Four broad soil classes of decreasing windthrow hazard were recognized in assessment of large-scale wind damage in Germany (Hütte 1968):

Poorly drained soils

Shallow brown soils

Normally rootable soils

Deeply rootable soils

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Shallow soils in which root development was restricted to 45 cm below the surface was found to be critical for windblow of mature Douglas-fir (Gratkowski 1956).

On sites with a high water table, root systems often have a flat table-like appearance on the bottom. When a water table fluctuates, the flooded roots of some species die, only to regrow downward as the water table recedes (Oliver and Larsson 1990). Spruce roots are killed during temporary periods of high water table (Savill 1976). A high water table may be present on some sites only intermittently after the spring thaw or during the rainy weather. The presence of endemic windthrow with flat root systems and signs of gleying in upper soil horizons may assist in diagnosis of these sensitive sites.

On sites with a high water table, uprooting is caused not only by the force of single gusts, but also by the duration of the wind storm. Such an uprooting action in Norway spruce trees was described on gleys with water table up to 45 cm from the surface as follows (after Hütte 1968):

> The main roots (lateral and supporting roots) do not penetrate into soil more than 10 to 20 inches (25-50 cm). Vertical (anchor) roots are either entirely absent or they penetrate sporadically up to a depth of 60 cm. When the spruce sway (wind speed 35-40 mph (55-65 kph)), the vertical roots which fasten the windward horizontal roots are separated from the mineral soil. If the lee side roots are thin, the spruce is uprooted by a strong gust.

> If the lateral roots are strong, movement of the tree is transferred to the root plate, which thus rises and sinks. Rising and sinking of the root plate may be repeated several hundred times during the storm. In the process, water is mixed with soil particles and washes soil particles from and below the root plate on both the windward and lee side of the tree. The supporting lee side roots are pressed deeper into the waterlogged soil, the tree is swaying more, and finally is overthrown.

In moist soils, tree swaying is marked by lower friction resistance of the roots than in dry soil; a 10% greater sway period of dominant Norway spruce was observed on moist soil than on dry soil (Mayer 1989).

Resistance of a tree to windthrow is also dependent upon the sheer strength—primarily the cohesion strength—of the soil in which it is growing. Dry sand has no cohesive strength and rooting in sand must be deep and widespread for stability (Busby 1966). Clay is very cohesive when dry but its cohesion becomes increasingly weaker with increased wetness. In fact, in all soils, sheer strength is inversely proportional to moisture content.

Since white spruce is a shallow-rooted species and forms flat root plates on moist soils, some of the above observations should apply to wet and intermittently wet soils in Boreal mixedwoods.

For example, the rise in soil moisture after harvesting an aspen overstory could seriously affect anchorage of released white spruce understory. Reduced evapotranspiration caused by harvesting the dominant component of the transpiring stand can have a twofold effect. First, in cases of moist soils, the soil may become waterlogged, thus losing anchoring strength. Second, the soil may become anaerobic, thus inhibiting root expansion and root growth of released spruce.

Residual trees continue to pump out extra water through evapotranspiration and thereby help keep moist sites from becoming anaerobic. Aspen and balsam poplar retained after logging may be critical for maintaining favorable conditions for root growth response and stability of white spruce understory.

5. Site Preparation

The method of site preparation used for the establishment of plantations also influences root architecture and soil strength, with consequent effects on plantation stability later in the rotation (Miller 1985).

Plowing can reduce lateral root spread and hence the stability of the trees (Booth 1974), particularly where ditches created by plowing are deep or water-saturated and inhibit root growth across them.

In areas where rooting depth is seriously restricted by a temporary high water table, the method of ground preparation is considered as important as thinning in its influence on windthrow. Methods that encourage wide-spreading root plate development are advocated, e.g., hand turfing rather than plowing (Savill 1976).

In shelterwood and seed tree systems, mechanical scarification (ground disturbance) can seriously damage roots and reduce their physical strength. If scarification is necessary, orient strips parallel to the prevailing direction of damaging winds. The same applies for the alignment of designated skid trails.

Wounding of roots by scarification can induce points of entry for root rot and butt-rot-causing fungi. White spruce seems to be quite sensitive—higher incidence of rot and stem breakage of white spruce was observed in residual stands 30 years after a shelterwood cut and subsequent blade scarification in the Boreal mixedwoods region (L. Brace, personal communication 1994).

H. WIND DAMAGE MANAGEMENT IN SILVICULTURAL SYSTEMS

1. General Principles

Implementing a silvicultural system is challenging since goals must include both maximizing silviculture objectives, such as regeneration and growth and yield, and minimizing losses. Consequently, protection against damaging agents, including wind, becomes an integral part of silvicultural systems and their design. In fact, in regions with recurring wind and snow damage, some silvicultural systems have evolved primarily for wind protection, and the use of other silvicultural systems has been severely constrained.

In the following, we discuss the general knowledge and principles of wind protection as they apply to different silvicultural systems. Four silvicultural systems—clearcutting, seed tree, shelterwood and selection—are discussed.

Emphasis is placed on information pertinent to the protection of released white spruce understory in a two-stage silvicultural and harvesting system (Brace and Bella 1988; Brace Forest Services 1992; Navratil et al. 1994). In terms of the type of silvicultural systems, the two-stage harvesting system falls in the categories of *Natural Shelterwood* and *Irregular Shelterwood*.

a. Clearcutting system

Clearcutting, from a wind protection standpoint, has the advantage of simplicity. Changing the spatial pattern and time sequence of clearcut areas can readily accomplish wind protection objectives. In a clearcutting system, wind-caused losses are primarily associated with an edge effect. Windthrow and other wind damage are usually limited to an area 8-20 m into the uncut stand or uncut strip from the cut edge. Techniques adopted to control wind damage in the clearcutting system are:

1. successive clearcuts proceed against the prevailing wind

2. cuts are made in narrow strips (20-100 m maximum)

3. strips are oriented at right angles to the prevailing wind direction

The technique of orienting strips perpendicular to the prevailing wind direction has limited application in areas where there is high probability of damaging winds coming from different directions.

In **progressive strip cutting**, the stand is divided into a number of cutting sections. Within each cutting section the felling progresses in strips that are perpendicular to the wind direction. The strips are cut at 5- to 10-year intervals. Cutting sections should have wind resistant edges or belts on the windward side whenever possible. Older roads and seismic lines with stand edges that have developed low branching and other wind resistance characteristics can be used for this purpose. Through long-term planning, a similar effect can be created by cutting lines the width of one tree height (10-15 m) through young stands 20-30 years prior to the main harvest schedule. This technique is called *severance cutting*.

The *interval* between successive cuts in progressive strips depends on the regeneration method and the rate of height growth of regenerated stands. The frequency of seed years and the rate of herbaceous and grass cover development will affect the cutting intervals if natural regeneration is used. Sufficient height growth of regenerated trees is necessary to protect the windward edge of the remaining stand. In a completed sequence of progressive strip cutting the wind-deflecting height profile of the regenerated stand will provide very high wind protection.

The *width of strips* can vary within a section to take advantage of the wind-resistant boundaries of natural openings and other edges. Narrow strips provide a greater protection to uncut strips by minimizing wind speed increase over the open cut area. However, strip width must also consider the light and temperature conditions required for the species to be regenerated.

In **alternate strip cutting**, which leaves every second strip uncut, the stability of uncut strips is affected by their length and width as well as the orientation and width of the clearcut strips. The width of clearcut strips influences wind speed and thus the incidence of wind damage on the windward edges of retained strips.

Uncut strips should be harvested as soon as effective regeneration is achieved. Longer retention of uncut strips increases the cumulative damage by windthrow, particularly when stands are overmature and showing signs of localized disturbance.

For light-demanding species, uncut strips can be much narrower if their role is only to provide a seed source and not the benefits of an improved environment for regeneration. This system of leaving narrow belts of seed-producing trees is transition into a **seed tree system**. When compared with leaving scattered seed trees in a uniform seed tree system, the advantage of leaving narrow belts or strips of trees may be a greater resistance against wind damage. This is likely more valid if belts contain a mixture of hardwood species.

When clearcut strips are narrow the residual strips do not suffer substantial wind loss. This held true, for example, for 30 m wide cut strips separated by 80 m of uncut strips in lowland black spruce stands in Minnesota (Heinselmann 1957). In black spruce stands in Northern Ontario, Fleming and Crossfield (1983) recommend the leave strips should be at least 40 m wide to reduce blowdown to an acceptable level. They found blowdown losses related to the height of the trees, density of the stands, ratio of stand edges to stand area and the topography of hills versus valleys. Similarly, Elling and Verry (1978) found wind-caused mortality in strip-cut black spruce to be a function of residual stand size, length of exposed edge and site index.

Concerning the location of the damage, the greatest amount of blowdown in alternate strip-cuts in black spruce stands was often located at the exposed corners of leave strips, where the wind can come from several directions. Hence, strips should preferably have blind ends that back on standing forest at the end of the cut strips (Jeglum and Kennington 1993). The same authors also found it useful to alternate the cut strips on opposite side of haul road so that the open ends do not lie directly across from one another.

In one of the older wind damage studies in Canada, Gilmour (1926) compared blowdown in Newfoundland black spruce stands harvested by clearcutting, clearcutting in 0.4 ha patches, clearcut strips (approx. 40 m x 130 m), seed tree and selection methods. Greatest damage occurred in the clearcut patches and strips.

The disadvantages of a clearcutting system with respect to wind damage management are three-fold:

a)   it produces even-aged systems that are in general more susceptible to damage by wind and snow

b)   it frequently elevates the water table on sensitive, moist sites which in turn makes trees more vulnerable to windthrow

c)   under intensive forest management, it tends to produce pure coniferous stands rather than the variety of species and structures found in more wind resistant original stands.

The primary advantage of clearcutting for wind damage management is the easy implementation of changes to layout and sequencing of harvesting. By properly orienting clearcut strips and by varying the width of clearcut strips, damage can be reduced to a minimum. Another advantage is that in clearcutting systems, the incidence of harvest injury to standing trees (that can cause stem and root rots which can lead to increased stem and root breakage) is very low compared to shelterwood and selection systems.

b.   Seed tree system

The seed tree system is used for light-demanding species with wind-dispersed seed. It is similar to clearcutting where all the mature trees are removed in one cut, except for about 10-25 seed trees retained per hectare.

Of all silvicultural systems, the seed tree method is most vulnerable to losses by windthrow. The sudden removal of protection provided by the whole stand makes the retained trees particularly susceptible to windthrow. Therefore windfirmness is a primary consideration in selecting seed trees. The seed tree method is not suitable for shallow rooting species like the spruces, nor is it applicable to any species growing on wet or thin soils which restrict rooting to the upper layers (Matthews 1989).

The most windfirm trees are usually dominants, with strong taper, deep live crowns and correspondingly strong root systems. When selecting Norway spruce seed trees, 90% crown length is recommended as the threshold of stability (Nielsen, personal communication 1990). It may be necessary to release the crowns of the potential seed trees by a preparatory cut or by a single-tree herbicide treatment of competing deciduous trees applied before the main harvest.

Since seed trees are sometimes retained to put on diameter and value increment as well as to provide seed, the losses due to windthrow can be particularly great. Leaving trees in narrow strips (as discussed earlier) or in groups may somewhat reduce the risk compared to leaving them singly dispersed in isolated conditions.

To reduce the probability of losses, the retained seed trees should be removed as soon as satisfactory stocking is achieved.

Despite wind damage risks, when careful choice of seed trees and species is used, the seed tree

method works very well. It has been applied successfully to ponderosa pine in western USA and in British Columbia and has alleviated problems with regeneration of western larch in the Kootenays in British Columbia. In the mountainous western USA the seed tree method is usually not applied for lodgepole pine regeneration because of susceptibility to windthrow (Alexander et al. 1983). In Boreal forests, it might have application in Jack pine stands in wind-protected areas.

c.   *Shelterwood systems*

In the shelterwood system trees from the main canopy are removed in a series of cuts designed to establish and grow a new stand under the shelter of the remaining trees. There are usually 2-4 fellings in the series including:

a)   preparatory cut—preparing for regeneration and improving wind resistance of the trees to be retained for future cuts

b)   seed cut—creating light and temperature conditions for regeneration

c)   removal cut(s)—removing the retained trees once regeneration is established

The preparatory cut and seed cut are sometimes combined, reducing the total number of cuts to as low as two.

If not properly executed, the gradual opening of the canopy by preparatory and seed cuts can increase the stand's sensitivity to windthrow damage. The preparatory cut should encourage the trees selected as seed-bearers to become windfirm through development of their crown and root systems. Under intensive management, the production of windfirm trees is achieved by thinning at intervals suitable for the gradual release of trees from competition prior to the preparatory cut or seed cut.

Under the **uniform shelterwood** system, the canopy is opened evenly throughout the cut unit. Uniform shelterwood is not suitable for shallow-rooted species in regions that are subject to severe winds. Norway spruce stands exhibit this characteristic, and a seed cut which uniformly opens the canopy makes it too susceptible to windthrow.

Wind damage in shelterwood systems is partially due to the loss of support from neighboring trees. To avoid isolation and exposure of the retained trees, the seed cut should be done carefully. It is also important that the period for regeneration establishment, and hence the time retained trees need to be kept, be as short as possible. To accomplish this, the conditions for regeneration should be favorable.

Pine species are adapted for the uniform shelterwood system, particularly in widely spaced stands that are naturally conducive to the production of windfirm trees. The system seems to work well for Scots pine, white pine, and also beech, in Europe; and ponderosa pine in British Columbia and western USA.

In wind-prone areas, uniform shelterwood can be replaced by **strip shelterwood** or **group shelterwood** systems. In **strip shelterwood**, the sequence of regeneration cuts proceeds in strips

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against the prevailing wind direction. As in strip clearcutting, the uncut strips provide shelter to the strips which have been opened.

A combination of strip shelterwood and group shelterwood systems have been successfully implemented in Europe where Norway spruce is regenerated in mixtures with fir or with beech, Scots pine and larch. The mixtures add wind resistance characteristics to the developing stand. Species composition is regulated by the rate at which the canopy is opened.

In the early stages of regeneration in the **group shelterwood system** there is a lower risk of wind damage than under the uniform system. During the later stages, however, as the remaining seed-producing trees become more isolated and exposed, the risk becomes higher for the group shelterwood system. The damage can be serious as gaps in the canopy become large. Protecting advanced regeneration in existing gaps may not only shorten the regeneration period, but can create windfirm edges in gaps and increase overall windfirmness of the stand. The advantage of a group shelterwood system is its ability to produce a species mixture which will enhance protection from both wind and snow. Although the group shelterwood system is not suitable for regions with strong recurring winds, it is superior to the uniform shelterwood system in these areas.

Potential value loss is one of the disadvantages for all shelterwood systems. Since the best stems (those of top quality and large diameter) are usually kept as seed trees to gain volume and value from increased light, any losses from windthrow can be costly unless the windthrown trees can be properly salvaged.

Selection of which seed-bearing trees to retain, and the total volume or basal area to remove are two critical decisions for wind protection in shelterwood systems. Selection criteria for retained trees should emphasize high live-crown ratio, low slenderness coefficient, no evidence of rot, absence of wounds, and dominant canopy position. For white spruce, large-full crowned dominant trees: are usually windfirm; are heavy seed producers due to their fully developed crowns; and because of their height advantage, they disperse seed over a wide area (Waldron 1965). Thinnings applied prior to the first cut or the first cut itself may be required to improve these attributes on the trees to be retained.

d.   *Irregular shelterwood system*

The irregular shelterwood system combines elements from the group shelterwood system and selection system. The objectives are to achieve high quality and volume by manipulating stand composition and structure of the indigenous forest types. The resulting stand is generally uneven-aged and diverse in structure and composition. As a result, high wind resistance is obtained.

The starting point in the cutting cycle is the selection of trees which are elite or dominant either naturally or as a result of stand tending. These trees are further released to become vigorous seed-bearers with good crowns and root systems and once in the open, will resist wind damage and gain large radial increments, thus increasing their value. These trees are retained for the duration of the regeneration period of 40-60 years or in some systems to the second rotation. Where practiced (e.g., Germany, Austria, Switzerland), the system provides the expected level of wind protection and meets other objectives. However, the system can be demanding to implement and requires an elaborate wood extraction network.

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e. *Selection system*

Selection harvesting removes single trees or small groups of trees throughout the stand. Immature trees as well as trees of usable size are removed. This results in an uneven-aged and irregular stand in which all the age and size classes are mixed and regeneration is continuous.

An irregular stand structure more fully supports the development of crowns and root systems than even-aged stands and helps decrease the slenderness coefficient of trees. Therefore, the stands resulting from a selection system are less liable to be damaged by wind and snow. Wind damage in selection systems is rare and is limited to single (usually the tallest) trees, creating localized, small disturbances. Since the stands managed by selection system retain a continuous forest cover there is no risk of water table rise after intermittent harvest, thus further reducing windthrow potential related to high soil moisture and associated shallow rooting.

f. *Wedge system*

A wedge system is claimed to provide a significant reduction in damage by wind and is said to be useful in solving some of the problems of windy, temperate region forestry. It is a type of strip system that can be implemented in both shelterwood and clearcutting modes where a high level of protection is required.

Strip cutting proceeds from a center, initial strip outwards in two directions. The tip of the wedge points to the prevailing wind direction. Strips are usually narrower toward the wedge tip and wider towards the wedge base, but they can be the same width along the full length of the strip (Figure 30). Extraction trails are located between the strips.

The wedge design and orientation reduces exposure of the uncut edges to winds coming from a wide range of directions. For this reason, it may also have application in protecting and building wind resistance of released white spruce understory under conditions of high wind damage risk.

2. Design of silvicultural systems to minimize wind damage to released white spruce understory

The silvicultural systems discussed here are pertinent to the two-stage harvesting, stand-level model described by Brace and Bella (1988) and tested in Alberta (Brace Forest Services 1992, Navratil et al. 1994).

As discussed in previous sections, foresters are normally concerned about wind damage to mature trees in the stand edges along the boundaries of harvested areas. The situation is different for white spruce understory trees, grown under an aspen canopy and protected during the harvest of the aspen overstory to be retained in open areas of cutblocks for the next pass of logging. A new approach to the design of wind protection measures is required for these emerging stands.

Wind damage to released white spruce understory is a major risk for three reasons:

1. white spruce understory trees have very poor wind stability due to their tree morphology having been formed under the canopy. The morphological attributes that

affect wind stability—crown shape, slenderness coefficient, size of root system—
are all influenced by the amount of light transmitted by the canopy.

2. white spruce understory trees which have developed in the absence of strong winds
    may lack necessary support mechanisms such as strengthening of the lee-side roots.

3. removal of the aspen canopy exposes understory trees in the open area of cutblocks,
    making them vulnerable to changing wind speeds and patterns.

Conceptual approaches for reducing wind damage in released white spruce understory fall into four
categories:

1. assessment of windiness in the region

2. assessment of tree wind stability—tree morphology of understory trees

3. measures to improve the windfirmness of understory trees **prior to** removal of as-
    pen canopy

4. measures to reduce wind damage in released white spruce **after** removal of aspen
    canopy

The first two categories apply to the pre-harvest planning and selection of prospective stands for a
two-stage harvesting system. As well, windiness in the region and estimated wind stability of
understory should indicate, for the designated silvicultural system, the level of wind protection
needed to prevent major losses.

Site evaluation in preharvest planning is an equally important component in selecting suitable stands.
Sites with high water tables should be avoided and the probability of water table rise after aspen
removal should be assessed.

a.   *Windiness in the region*

Windiness of the region, particularly the probable occurrence of high-speed winds and their direc-
tional characteristics, must be known before wind-risk management is implemented and before
appropriate silvicultural systems can be designed.

In several countries, wind zones have been delineated according to the incidence and severity of
strong wind conditions. In Britain, for example, wind zones have been formulated using long-term
meteorological records and from attrition of exposed flags (tatter flag system) (Miller 1985).

Since most of windthrow damage is associated with gusting winds, the approach in Alberta was to
characterize and determine the probabilities of high wind gusts. The analysis of wind statistics
across Alberta was specifically commissioned for this purpose. It focused on determining the re-
turn periods for maximum gusts and the directional analysis of annual and seasonal maximum
winds (Flesch and Wilson 1993).

The return periods indicate typical periods between extreme wind events. This knowledge is essen-
tial in estimating the window available for tree stability improvement over time and for planning
sequenced harvesting passes. Table 7 summarizes the return periods for the major forest areas and
locations in Alberta where long-term records were available.

Table 7: Return periods for extreme windspeeds at various Alberta locations.

	Wind Speed (km/h)	Return Period (years) Annual	Return Period (years) Spring	Return Period (years)	Windspeed (km/h) Annual	Windspeed (km/h) Spring
High Level	50	1.0	1.0	2	78.8	60.2
	70	1.3	6.6	5	90.6	67.9
	90	4.7	115.2	10	98.5	73.0
	110	29.1	-999.0	20	106.0	77.9
	130	194.1	-999.0	50	115.7	84.3
Peace River	50	1.0	1.0	2	84.4	74.8
	70	1.0	1.4	5	91.2	83.2
	90	4.2	11.6	10	95.8	88.8
	110	100.5	163.7	20	100.1	94.2
	130	-999.0	-999.0	50	105.8	101.1
Edson	50	1.0	1.0	2	80.7	68.0
	70	1.1	2.4	5	90.2	77.0
	90	4.9	23.2	10	96.6	83.0
	110	46.9	279.1	20	102.7	88.8
	130	494.5	-999.0	50	110.6	96.2
Calgary	50	1.0	1.0	2	108.1	96.9
	70	1.0	1.0	5	116.1	105.9
	90	1.0	1.2	10	121.3	111.9
	110	2.4	8.0	20	126.4	117.6
	130	33.1	93.2	50	132.9	125.0
Slave Lake	50	1.0	1.0	2	96.5	80.1
	70	1.0	1.0	5	108.4	87.5
	90	1.4	7.1	10	116.2	92.4
	110	5.8	140.7	20	123.8	97.1
	130	35.7	-999.0	50	133.6	103.2
Grande Prairie	50	1.0	1.0	2	99.5	87.2
	70	1.0	1.0	5	108.7	97.0
	90	1.1	2.5	10	114.7	103.5
	110	5.8	20.7	20	120.5	109.7
	130	64.0	204.0	50	128.0	117.8
Fort McMurray	50	1.0	1.0	2	78.0	66.3
	70	1.2	2.8	5	88.3	75.1
	90	5.9	30.8	10	95.1	81.0
	110	49.2	397.5	20	101.7	86.6
	130	439.0	-999.0	50	110.1	93.8

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The following is an example of the interpretation of Table 7 data:

In Peace River, on average, wind speeds of 91.2 km/h can be expected every five years; while in Grande Prairie, wind speeds of 99.5 km/h are likely to occur every two years, thus suggesting more severe limitations for protection of white spruce understory based on five-year sequencing of harvest.

To calculate return periods for non-measured locations, the authors (Flesch and Wilson 1993) recommend that it is preferable to interpolate between stations as opposed to extrapolating from any one station, and that the data should not be extrapolated to areas of non-uniform terrain (i.e., foothills areas).

Seasonal differences were analyzed since variable soil moisture and frozen ground affect soil strength and anchoring of trees. Seasonal differences were minor with a slightly greater likelihood of high speed gusts in the north and south, and in the summer in central portions of the province.

The directional categorization of maximum winds is essential for spatial design of harvesting and silvicultural systems. Longitudinal axes of cutblocks and strips should be oriented perpendicular to the prevailing wind directions and harvest sequences should progress against the prevailing winds.

In Alberta, the predominance of extreme winds is from the west and northwest (Figure 18). In some regions the most frequent direction of maximum gusts is clearly delineated. In Peace River and Grande Prairie 79% and 91% of wind gusts are from a westerly and northwesterly direction respectively. In the Edson area the prevailing winds are northwest.

Orientation of cutblock layout should consider these differences; however, one should recognize that topography and stand structure can provide local changes in the direction of wind gusts.

Length of bars represents frequency of
occurrence in each direction.

Each concentric ring represents a 10%
increment in frequency
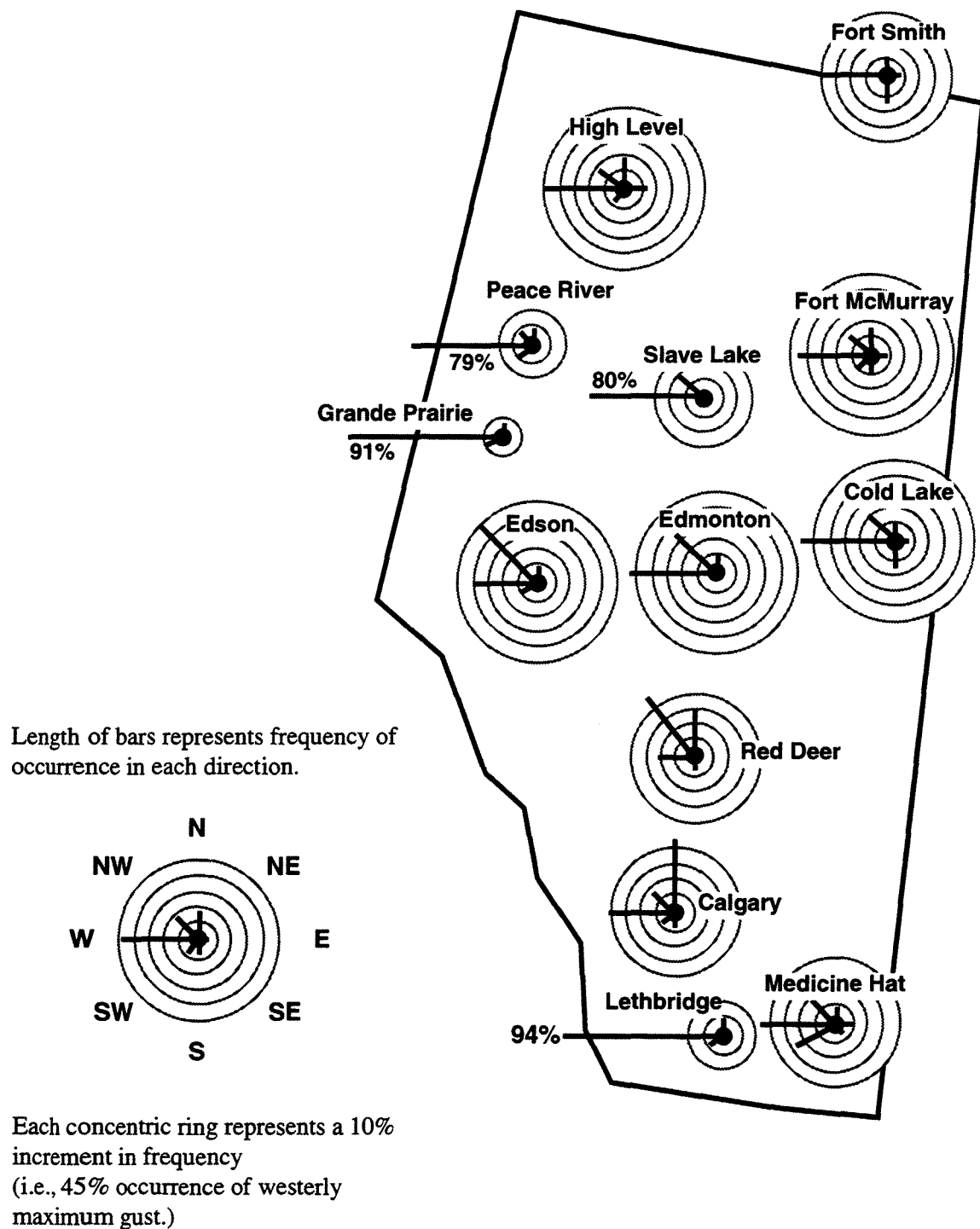(i.e., 45% occurrence of westerly
maximum gust.)

Figure 18.   Directional frequencies (wind rose) for annual extreme wind gusts in Alberta
(Flesch and Wilson 1993).

b. *Wind stability criteria of white spruce understory*

The critical limits for tree stability variables may vary according to local conditions such as site, surrounding stand structure and recurring winds. The great variation in these factors increases the difficulty of stability prediction. Some generalized guidelines have been developed for Norway spruce (see Section E).

Critical values for white spruce and other conifers of the western Boreal forest have not yet been tested, although current experimental work is designed to clarify the relative importance of the tree variables involved. In Alberta, preliminary results from the white spruce understory trials in progress show differences in damaged and undamaged trees measured after several years of wind exposure (Brace Forest Services 1992, Navratil et al. 1994). Results like these may indicate a potential for development of guidelines and a hazard rating system specific to white spruce understory.

c. *Stand structure of white spruce understory*

Height structure and spatial distribution of white spruce understory is usually highly irregular. In white spruce understory stands after aspen removal, there are many openings, trees are of uneven heights, and clumps of trees are of different sizes and densities. Windthrow is in general related to the degree and extent of interruptions to the forest canopy. White spruce understory may have a stand structure conducive to increased turbulence and windthrow. It may in fact lack many stand stability features.

On the positive side, clumps of white spruce can provide the mutual support of neighbors which helps reduce swaying. The presence of sporadic, larger trees may be equally beneficial. A large sized tree which has developed in a canopy opening should have better anchorage, a long crown and low slenderness coefficient. Trees with such characteristics provide a backbone for stand stability by damping out some of the wind effects on neighbor trees and are termed "stability trees" (e.g., Kuiper 1986). Stability trees are important in both small and large clumps. Roots of neighboring trees are often interlocked and one tree can uproot several surrounding trees. Pre-harvest spacing aimed at the development and subsistence of stability trees could reap two-fold benefits by maximizing both wind protection and growth and yield.

Height variations in clumps of white spruce can also be advantageous for another reason. All trees do not swing together because sway period depends on height. With a strong gust, only some trees would have their swing magnified to the critical point of windthrow.

Clumps of balsam poplar and aspen trees interspersed in white spruce understory may directly influence windthrow. Leaving clumps or narrow bands of aspen and balsam poplar have been considered in the design of silvicultural system as means of white spruce understory protection. The function of uncut or partially cut strips with residual aspen and balsam poplar in reducing wind speed and turbulence and thus protecting white spruce understory could be critical in high hazard situations. Hence, a brief, general description of windbreak effects follows.

d.   Residual strips as windbreaks

In agriculture, microclimate changes such as wind speed and turbulence in the lee of shelterbelts have been studied extensively both at full scale and in models (MacNaughton 1989). There appear to be no studies of wind break effects in reducing wind damage in forest stands. The general principle may be drawn from the studies in agriculture, but it should be recognized that winds over forests are more turbulent than winds over open fields. The more turbulent the wind is in the open, the less is the protection offered by a windbreak.

The following generalization is largely based on two comprehensive review papers of shelterbelts in agriculture by McNaughton (1989) and Kenney (1992). Observations pertain to narrow, thin windbreaks with width less than height. There is the prevailing opinion that wide belts (width height) give similar shelter to narrow belts (width < height) of similar porosity (McNaughton 1989). Orientation of windbreaks is considered perpendicular to the prevailing wind direction.

The wind-break effects of interest to us are the shelter quality—reduction in wind speed and severity of turbulence—and shelter extent—the area or distance covered by a shelter. These two traits are mainly affected by windbreak porosity and windbreak height.

In the case of a dense coniferous windbreak, the air striking it pools up against the barrier, rides over the barrier and creates a zone of the lower pressure on the leeward side. This zone of lower pressure draws the air down, thus shortening the sheltered area and possibly creating eddies and turbulence. There is a dramatic reduction in the wind speed close to the windbreak but the open-field wind speed is regained in a short distance (Figure 19).
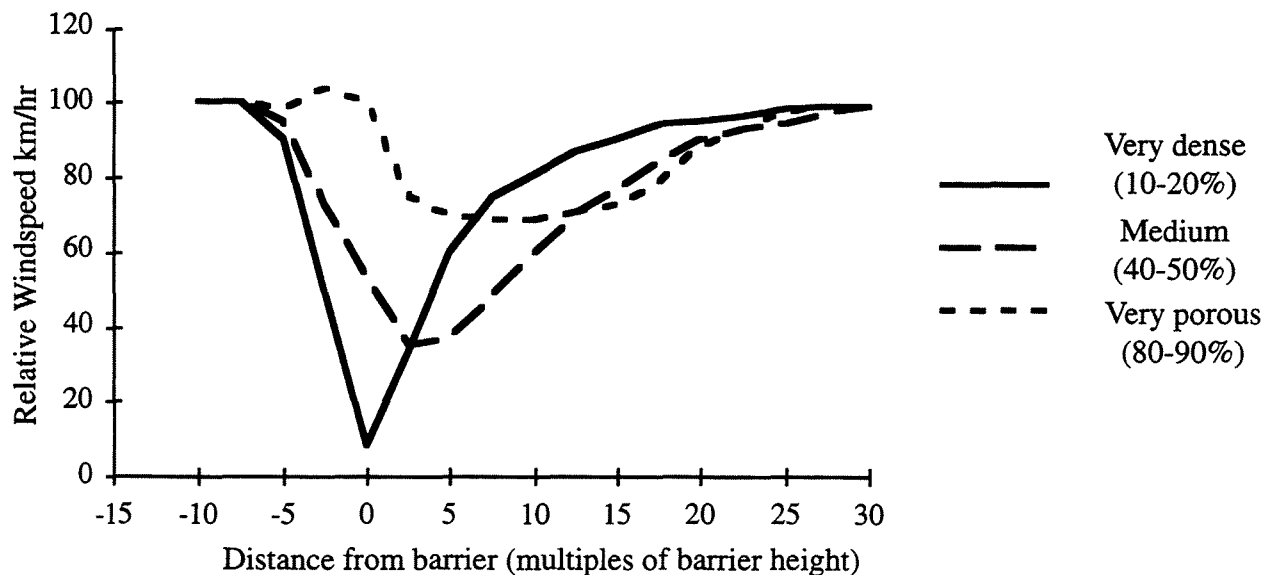

Figure 19.   The relationship between barrier porosity and the reduction in windspeed (after Kenny 1992).

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More porous barriers allow more air to pass through them, so the flow of air over the top and down behind the windbreak is reduced. The recovery of wind speed to the open-field speed is gradual, resulting in a relatively large area of protection, It is generally accepted that the maximum extent of shelter is created by a barrier with a porosity of 40-50% (references in Kenney 1992).

It may be noted from Fig. 19 that very porous windbreaks may result in a wind-speed increase immediately behind the windbreak due to the jetting of air through gaps in the windbreak.

Poplars, and hardwoods in general, tend to have a very low crown porosity at their base due to the natural tendency to self-prune. Deciduous trees also have very high porosity in the leafless state. The problem can be corrected by shrubs filling this lower level (Kenney 1992).

In the designs of silvicultural systems where strips of aspen and balsam poplar are retained to protect white spruce understory the effectiveness of a strip could be managed by varying its porosity.

The deciduous nature of aspen and poplar will result in porosity levels varying with the season. High levels of porosity mean less effectiveness in reducing wind speeds prior to leafing out in the spring, which could coincide with high soil moisture after the snow thaw that reduces the anchoring strength of soil. To alleviate this risk and also to fill the lower level of the windbreak, white spruce or other conifers such as balsam fir, over a range of heights, should be kept as a component of the strips.

Assuming that a windbreak consisting of aspen and immature white spruce has a medium 40-50% porosity in the leaf-out state, the approximate 50% reduction in wind speeds would occur for the distance of about 7 tree heights (based on the relationship in Figure 19).

It should be recognized that forests in general create more drag and generate more turbulence than open agricultural fields. The enhanced turbulence could shorten the zone of reduced speed compared to that observed in agricultural fields.

Notwithstanding the above, the approach of leaving uncut strips for the purpose of protecting released white spruce may have considerable merit, particularly when combined with other systems like shelterwood and alternate clearcut strips. Several such combinations are being field-tested in Northern Alberta on the Hotchkiss River project (Navratil et al. 1994) and should demonstrate the potential of narrow strips as windbreaks in a forestry setting.

e.   Improvement of wind stability of white spruce understory through density management

Establishing long crowns at a young age and maintaining low slenderness coefficient have been shown to be prerequisites for minimizing wind risk in coniferous (primarily Norway spruce) stands in Europe.

The controlling factor to crown length and slenderness coefficient is the proximity to neighbors casting side shade, leading ultimately to crown closure. The onset of crown closure occurs when the branches first begin to slow down because of lateral confinement. Time of crown closure and size of the living crown are directly related to spacing in single-species, even-aged stands (Oliver and Larson 1990).

Crown growth and the effects of proximity to other white spruce trees were modeled by Mitchell (1969) and have formed the essence of the Tree and Stand Simulation (TASS) model.

In a white spruce understory that has considerable variability in height, density and spatial distribution, the amount of neighbor tree influence on crown size and other attributes of wind stability may be difficult to ascertain.

Density management treatments recommended for wind stability improvement in even-aged spruce stands might not be as applicable in white spruce understory. On the other hand one-time spacing in white spruce understory with densities over 1000 trees/hectare could provide considerable gains in growth and yield (Brace Forest Services 1992) and most likely in stability as well.

The best candidate for spacing would be dense clumps of spruce that naturally form in small size openings after localized disturbance. Spacing should be implemented with care, selectively releasing the best crop trees. Under dense conditions, as are often found in white spruce clumps, trees lean on each other for mutual support. Removal of some trees may cause temporary instability (Groome 1988). However, careful treatment aimed at favoring stability trees would increase the overall, long-term stability of a clump.

For the best results, spacing could be combined with shelterwood systems and completed under the protection of a partial aspen canopy. By combining spacing and shelterwood the risk of causing temporary instability by spacing would be eliminated. Improved light conditions under shelterwood would improve tree morphology, resulting in both a higher level of wind stability and faster growth response after the final removal of aspen canopy.

f.   *Response of white spruce understory to the removal of aspen canopy*

When understory trees are released from overstory competition, their response can be variable: they may die, exhibit growth delay, or grow more quickly. Shade-tolerant trees, such as white spruce, may grow vigorously upon release from the high shade of an upper canopy. The success of release depends on good vigor, and large, live crowns with many branches and buds (Oliver and Larson 1990).

A tree's vigor, live crown ratio and, in turn, wind-resistance attributes of stem and roots, are greatly affected by the available growing space and light. Since tree tissues have different priorities in receiving available photosynthate for growth, not all tree parts grow at an equal proportional rate. Diameter growth has a lower priority for allocation of photosynthates than height growth and therefore slows down earlier than height growth under light limiting conditions. That is why trees growing under competition often develop spindly stems and high slenderness coefficient (e.g., Larson 1963, Navratil and MacIsaac 1992).

Response to release and improved light conditions will depend on crown expansion which in turn will gradually provide the photosynthates that enable the tree to grow faster in diameter. The increase in diameter growth and corresponding structural growth of roots leads to more stable trees. Hence the increased diameter growth may serve as an evidence of a tree's ability and the existence of conditions favorable for response to a silvicultural treatment.

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Lieffers et al. (1993) showed that white spruce saplings were able to quickly acclimate to increased sunlight when released from hardwood competition. There was no evidence of a reduction in photosynthetic capacity following removal of overtopping hardwoods.

Observations from the trials of a two-stage silvicultural system in Alberta suggest that white spruce understory trees react well to aspen canopy removal. No signs of chlorotization or loss of needles were observed on released white spruce and height and diameter growth increases were evident within two years of release (Brace Forest Services 1992).

Furthermore, in the same stands there was a decrease in slenderness coefficients of the released spruce over five years since harvesting. Reductions in the height/DBH ratios occurred consistently in all height classes and density classes in all three sites (Table 8) (Navratil et al. 1994).

Table 8.   Changes in slenderness coefficient of released white spruce five years after harvesting by height classes and density classes (From Navratil et al. 1994).

AREA	YEAR	Height Class (m)						Density Class (trees/ha)											
		1.31-2.5	2.51-5.0	5.1-7.5	7.6-10.0	10.1-12.5	>12.6	1-400	N*	401-800	N	801-1200	N	1201-1600	N	1601-2000	N	>2000	N
Drayton	1988	204	103	88	*85	74	68	98	190	117	101	121	43	110	24	112	12	109	19
Valley	1993	115	86	76	74	67	62	76	190	87	101	88	43	93	24	99	12	100	19
	Change %	-44.0	-16.5	-13.6	-13.0	-9.5	-8.8	-22.5		-25.6		-27.3		-15.4		-11.6		-8.2	
Hinton	1988	223	116	100	97	88	81	118	180	117	147	117	73	138	74	122	47	128	194
	1993	144	96	88	86	81	73	83	179	92	147	91	73	108	74	100	47	110	193
	Change %	-35.4	-17.4	-12.0	-11.3	-7.9	-9.9	-19.7		-21.4		-22.2		-21.7		-18.0		-14.1	
Whitecourt	1988	218	110	96	96	94	94	118	145	139	106	150	47	134	37	157	18	147	44
	1993	99	83	79	79	86	81	78	144	88	106	97	47	92	37	95	18	96	44
	Change %	-66.0	-24.0	-18.0	-18.0	-8.5	-13.8	-33.9		-36.7		-35.3		-31.3		-39.4		-34.7	

*N-sample size

This provides circumstantial evidence that:

a)   the conditions of high shade under the aspen canopy did not affect the physiological and morphological attributes of white spruce that would alter its potential for height and diameter growth after release.

b)   adequate photosynthate production and allocation of photosynthates to diameter growth occurred in the released spruce.

c)   in the treated stands, stand and environmental conditions (i.e., spacing, light, moisture, and nutrient availability) were favorable to white spruce crown development and growth.

In the same stands there was negligible or no increase in windthrow between 3 and 5 years after aspen canopy removal. The absence of significant windthrow in 4-5 years after release in conjunction with the observed trend of decreased height/DBH values, strongly indicates that spruce stability improved as a result of crown, stem and root growth.

The improvement of wind stability in five years since release is of critical importance in silvicultural planning. The stability improvement of white spruce in response to improved light conditions and wind stimulus gained in 5 years after release has been one of the major assumptions used in the design of silvicultural and harvesting options, currently being to be tested in Northern Alberta.

3.   Silvicultural and harvesting systems for minimizing wind damage in white spruce understory

Silvicultural systems for reducing wind damage in released white spruce understory incorporate two approaches—those applicable *after* and those applicable *before* aspen canopy removal.

a.   After aspen canopy removal

Silvicultural options that minimize wind losses in white spruce understory after aspen canopy removal utilize the sheltering effects of uncut stands, uncut windbreak strips and tree clumps as discussed in Section G and H.1.

The major assumption in this approach is that for a distance of two stand heights from the windward edge of the clearcut strip the maximum wind speed will not be greater than 50-70% of the open field wind speed. Additional reduction in wind speed in some designs is assumed to occur due to windbreak effects of retained, uncut strips.

Sequencing of the harvest passes (cuts) is based on the second assumption, that a period of 5 years since release will be adequate to improve tree stability of released spruce and consequently reduce probability of damage. Arguments in support of this assumption are discussed in Section E.3 and H.2.4.

b.   *Prior to aspen canopy removal*

Silvicultural and harvesting options that aim to improve windfirmness of white spruce understory prior to aspen canopy removal presume that tree stability improvement is induced by partial canopy removal and increased light reaching the understory. This is largely a conjectural assumption with respect to white spruce although Lieffers and Stadt (1994) observed a decrease in white spruce slenderness coefficient with increasing light intensity under aspen and white spruce overstories.

There is also a largely arbitrary assumption used here that the removal of 50% of the basal area of aspen overstory will adequately increase light and provide enough wind stimulus for spruce to improve tree stability characteristics.

Based on the above assumptions, an array of the silvicultural system designs, with incremental wind protection levels varying from no protection to very high protection have been developed. The intent was to develop a spectrum of systems to choose from for a particular wind damage risk, as described by its location and stand condition (windiness of the area, height and slenderness coefficient of understory, site) and harvesting technology available. The wind protection level provided by the designed systems, and harvesting difficulty when using feller-buncher felling is given in Table 9. Several original designs were adapted to suit the harvesting technology of feller-buncher while being implemented in a field trial in Northern Alberta (Navratil et al. 1994).

Wind protection aspects of each of the systems are described in the following examples and Figures.

Table 9: Silviculture systems for reducing wind damage in white spruce understory (in part from Navratil et al. 1994).

System	Type of protection	Level of protection	Level of harvesting difficulty [1]
Clearcut; total removal of aspen canopy	None	None	Easy
Clearcut; total removal of aspen canopy; some clumps of standing balsam poplar and aspen	Mutual support of neighbor trees and reduced wind speed within clumps	Low, varies with size and spatial distribution of standing residuals	Easy
Clearcut; removal of the aspen canopy with retained long windbreaks of aspen/ balsam poplar	Reduced windspeed on lee side of windbreaks	Medium to high, varies with porosity and distance between windbreaks	Easy
Alternate strip cutting in two passes 50 m wide 100 m wide 150 m wide	Sheltering effect of stand on windward side	High after first pass, low after second pass, varies with width of strip	Difficult Moderate Moderate
Uniform shelterwood, 50% removal of basal area	Improved stability of understory between 1st and 2nd passes	Medium	Not compatible with feller-buncher harvesting
Modified uniform shelterwood, 1 pass	Improved stability of understory and sheltering effect of retained narrow strip	Very high	Moderate
Modified uniform shelterwood, 2 passes	Improved stability of understory and sheltering effect of uncut strip in the first pass	Very high after the first pass Medium after the second pass	Moderate
Combined shelterwood strip system, 2 passes	Sheltering effect and improved stability of understory	Medium to high	Moderate to difficult
Combined shelterwood strip system, 3 passes	Sheltering effect and improved stability of understory	High	Moderate to difficult
Progressive strip clearcutting	Sheltering effect and height gradient of spruce deflecting wind	High	Moderate to difficult
Wedge strip cutting	Sheltering effect and height gradient of spruce deflecting wind in a wide angle of directions	Very high	Unknown

[1] Feller-buncher felling

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I.   SILVICULTURE SYSTEM DIAGRAMS

1.   One-pass overstory removal

A one-pass removal of the entire deciduous and coniferous overstory can be made while protecting white spruce understory. (Figure 20). There is no wind protection for released spruce except in the narrow band adjacent to the windward edge of the cutblock.
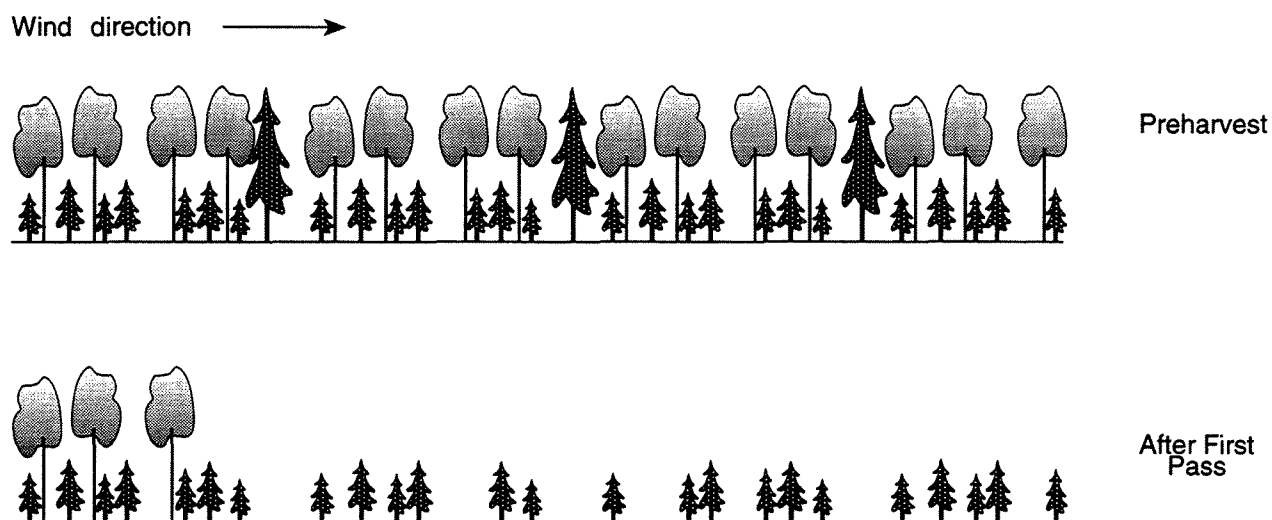

Figure 20.   One-pass overstory removal while protecting white spruce understory.

2. Modified one-pass overstory removal

A modified version of one-pass removal retains narrow strips or clumps of uncut deciduous as repetitive windbreaks. In the design below (Figure 21) from the Hotchkiss River project using feller-buncher technology, the uncut strips were 5 m wide resulting in about 15% of the merchantable deciduous timber being sacrificed.
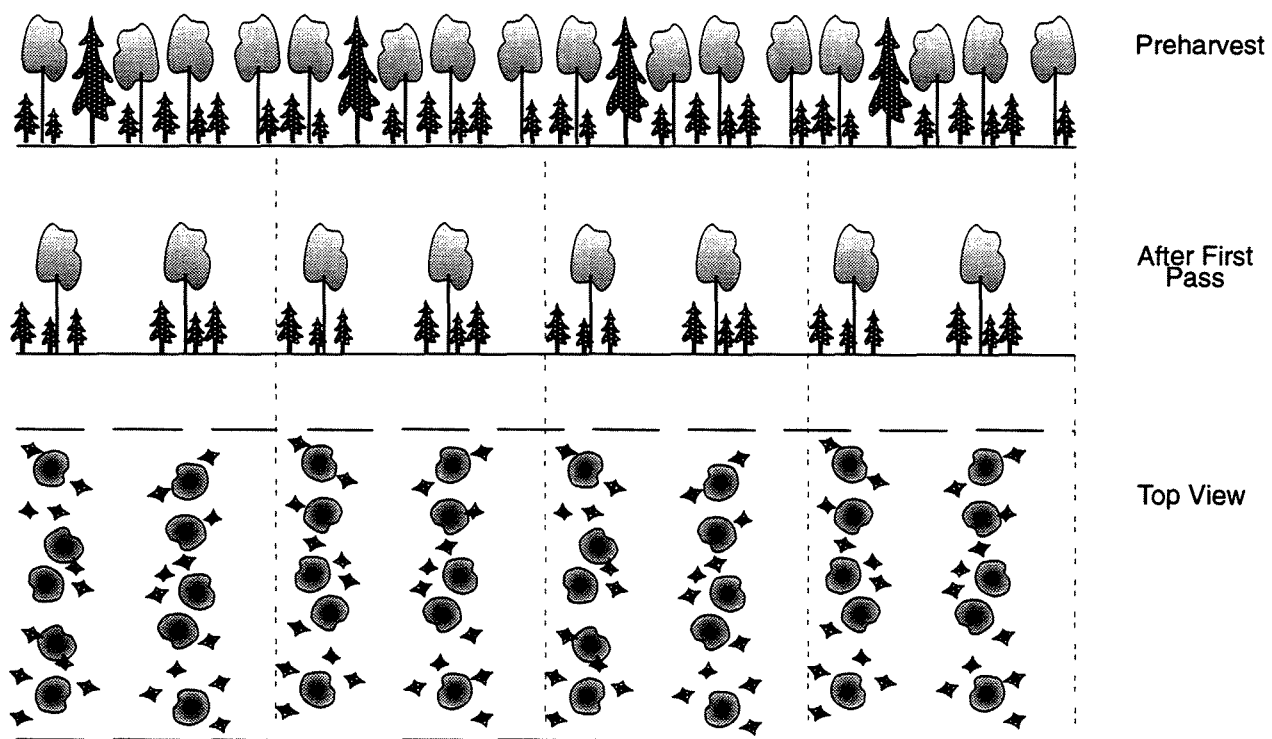

Preharvest

After First Pass

Top View

Figure 21.   Modified one-pass overstory removal with retained uncut, narrow strips as repetitive windbreaks (from Navratil et al. 1994).

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3.   Two-pass uniform shelterwood

Two-pass **Uniform shelterwood** uses the approach of improving windfirmness of white spruce understory before the final harvest of the partially retained aspen canopy (Figure 22). About 40-60% of the stand's merchantable deciduous and coniferous volume is removed in the first harvest. During the time between the first and second harvests, improvement in wind stability of immature spruce is expected.

Wind   direction ⟶

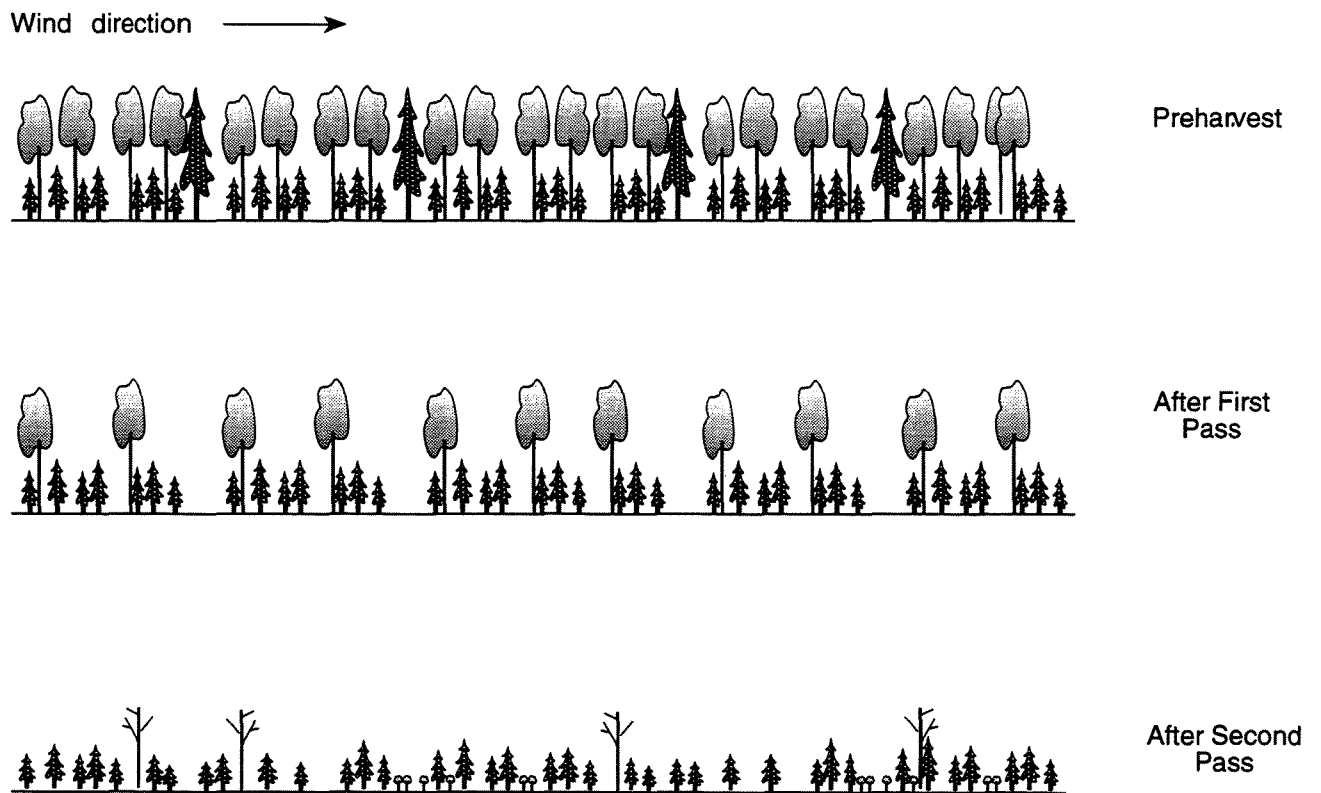Preharvest

After First
Pass

After Second
Pass

Figure 22.   Two-pass uniform shelterwood system.

A modification of the two-pass uniform shelterwood to suit feller-buncher harvesting technology was implemented in the Hotchkiss River project (Navratil et al. 1994) and is illustrated in Figure 23.
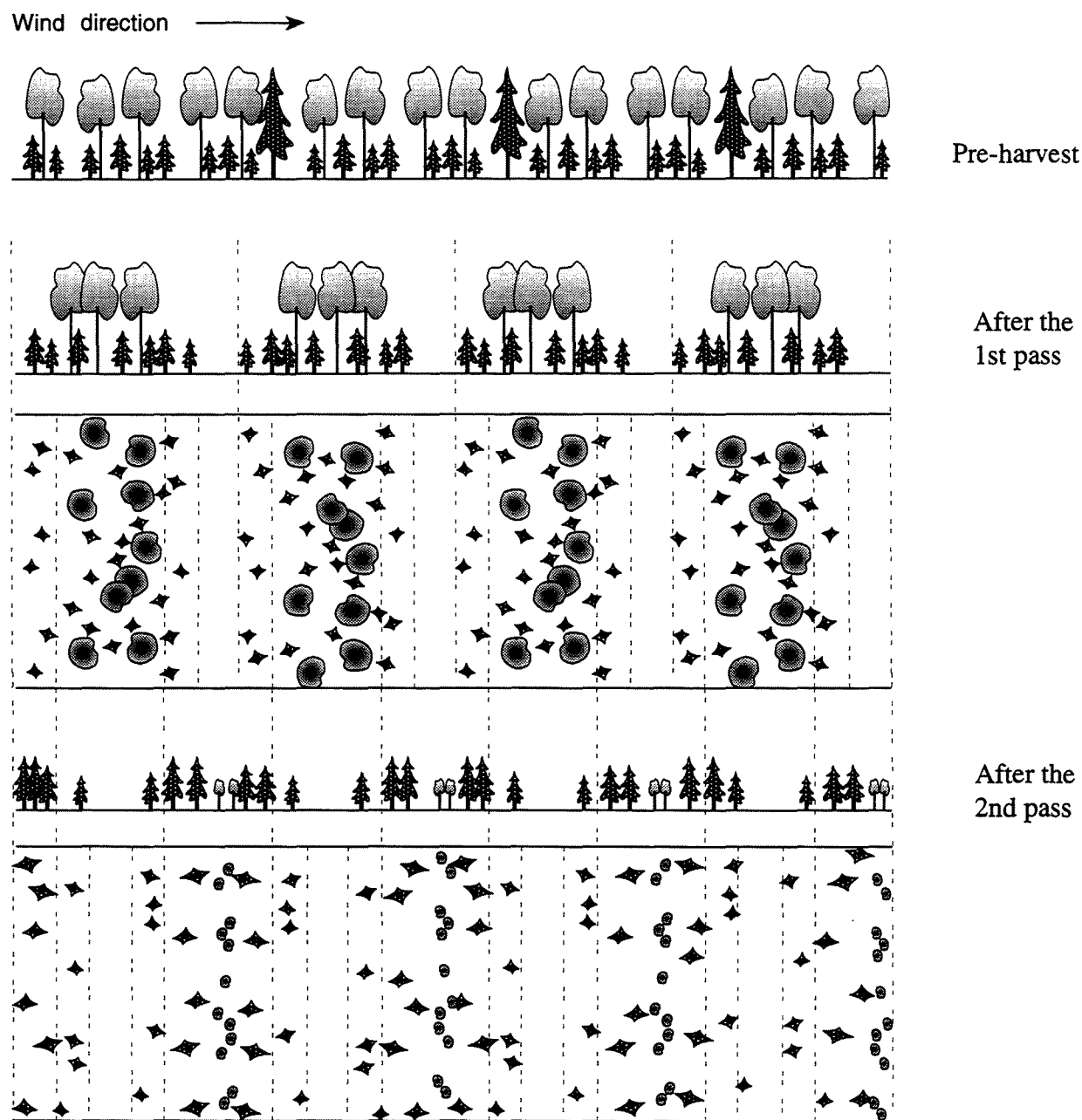

Figure 23.   Two-pass modified uniform shelterwood adapted to feller-buncher harvesting (from Navratil et al. 1994).

4. Two-pass combined strip shelterwood

The combined **strip shelterwood** system combines three approaches:

a.   the sheltering effect on the lee side of the retained strips (or stand)

b.   progressive cutting against the prevailing wind direction

c.   improvement of windfirmness of white spruce under a partially opened canopy

The spatial layout (Figure 24) divides the stand into harvesting segments and strips oriented longitudinally against the prevailing wind direction. Strip width can vary to a maximum 75 m, depending on windiness conditions.
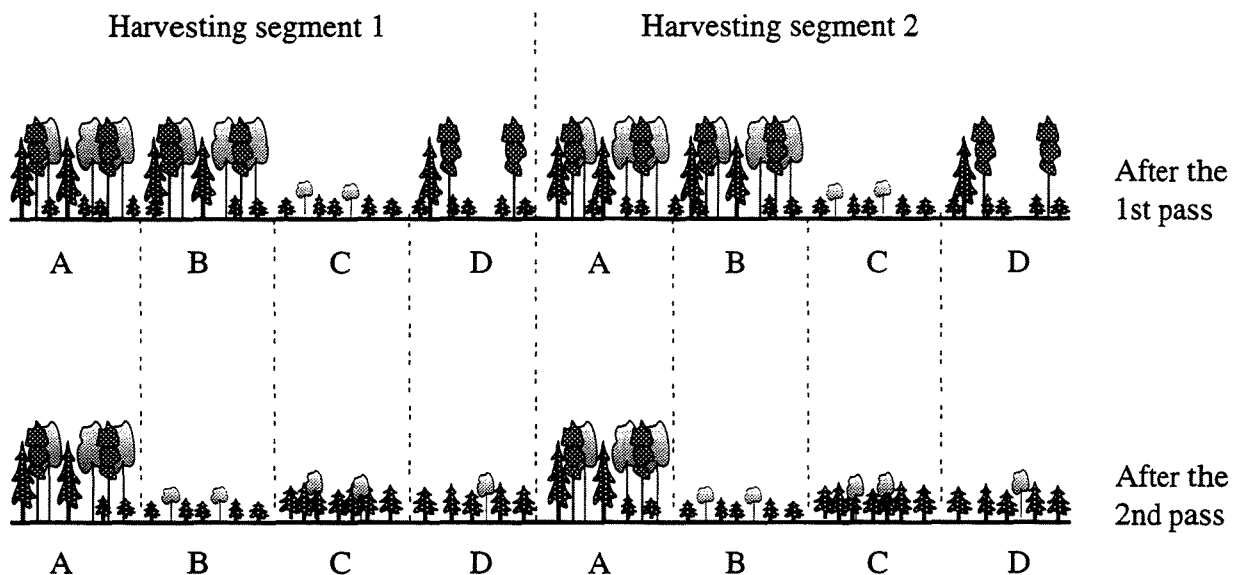

Figure 24.   Two-pass combined strip shelterwood system.

In the first pass, strips "C" are clearcut (total canopy removal) while retaining white spruce understory. Strips "D" are partially cut, retaining approximately 50% of the canopy, and white spruce understory is protected and retained.

In the second pass, strips "B" are clearcut and in strips "D"to remaining 50% of the residual canopy is harvested. The role of strips "A" is to provide a sheltering, windbreak effect for white spruce understory on the lee side of the strips. This presents two options for harvesting:

In the first option, merchantable spruce is harvested within the strip in the second cut, leaving a windbreak strip composed of mature aspen and balsam poplar and immature, small size understory spruce. At the time of the rotation harvest, 40-60 years later, the small size spruce in the understory will reach merchantable size. Aspen and balsam poplar volume may be sacrificed because of accelerated mortality and deterioration of exposed trees. In this option the width of the "A" strips in the layout can be narrow.

The second option can be a delayed liquidation harvest of the "A" strips until approximately 10-15 years after the second cut. The elapsed time between the second pass and liquidation harvests is required to gain height growth in strips "D," which will now provide a sheltering effect to the released white spruce in "A" strips after aspen canopy removal.

Both options assume sheltering protection by stand or topography on the farthest windward side of the harvesting segments "1."

5.   Three-pass combined strip shelterwood

The **three-pass combined strip shelterwood** system is based on the same concepts as the two-pass system (Figure 25). It is expected to provide a very high level of protection for retained understory spruce because of the combined effects of a) sheltering in narrow strips; b) stability improvement through partial canopy removal; c) windbreak effects from uncut strips ("A" and "B") remaining after the second pass; d) lengthened time for height growth of retained spruce released in the first pass (strip "C"). The major advantage of the three-pass system relates to the effect described under d). Taller spruce in the strips "C" and "D" will provide sheltering protection to white spruce exposed after the total removal of canopy in strips "A" in the third pass.
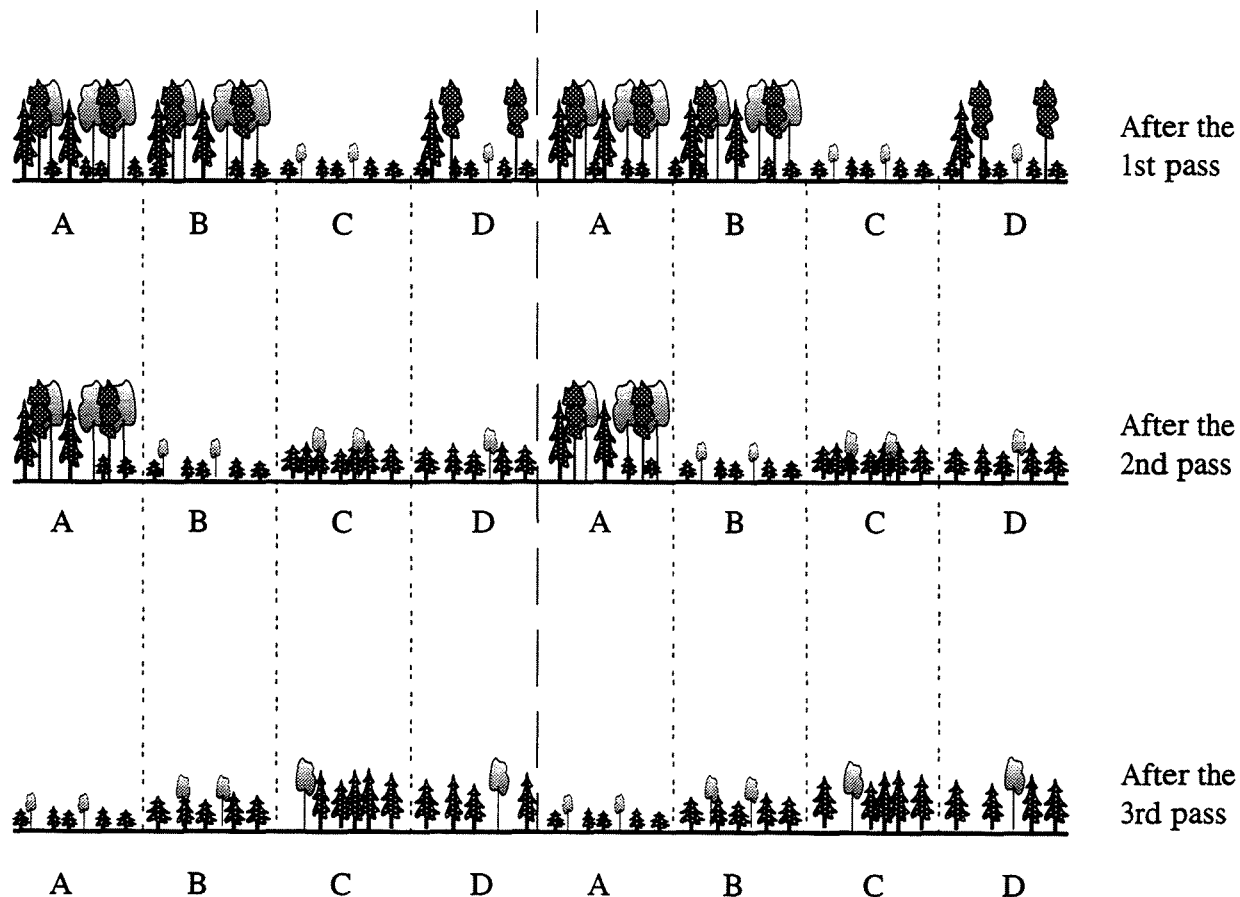

Figure 25.   Three-pass combined strip shelterwood system.

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The versions of two-pass and three-pass combined strip shelterwood adapted to feller-bencher harvesting as implemented in the Hotchkiss River project are illustrated in Figure 26 and Figure 27.
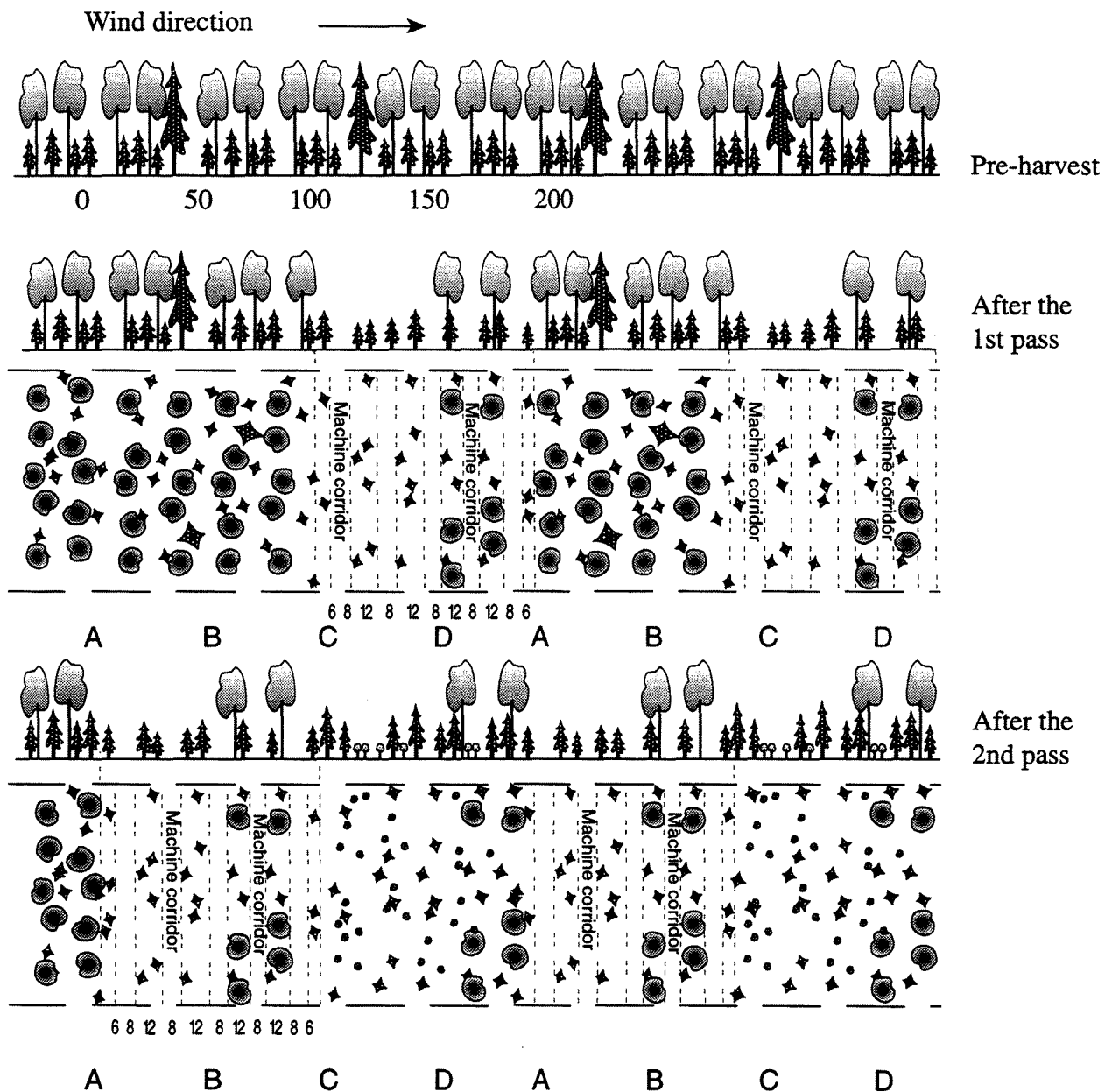

Figure 26.   Two-pass combined strip shelterwood (50m) (from Navratil et al. 1994).
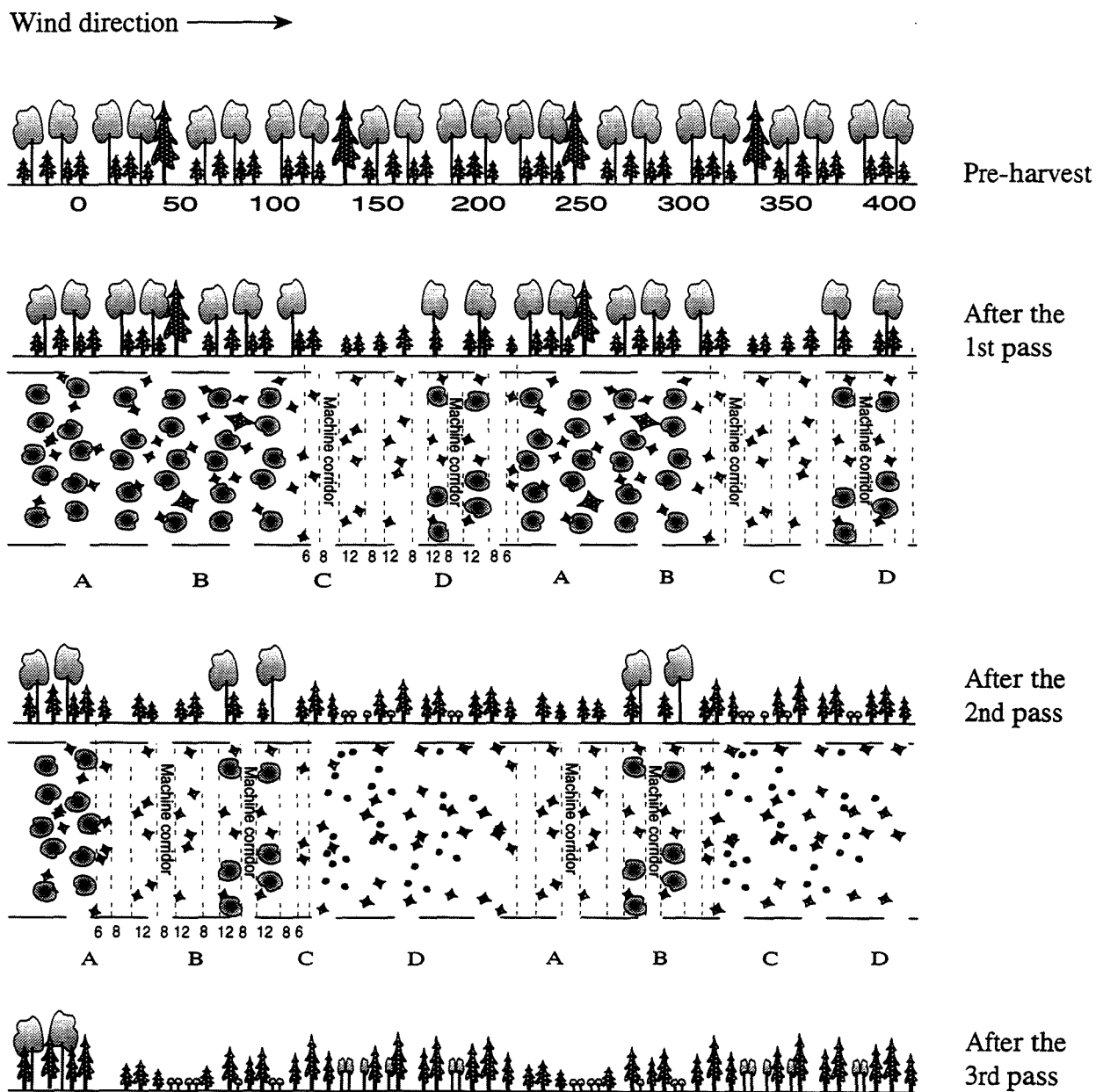
Wind direction ⟶

Pre-harvest

After the
1st pass

After the
2nd pass

After the
3rd pass

Figure 27.   Three-pass combined strip shelterwood (50m) (from Navratil et al. 1994).

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6.   Alternate strip clearcutting

Alternate strip systems provide low to medium levels of protection to released white spruce after the first pass, depending on the width of strips. The protection is provided by sheltering effects of the uncut strips (Figure 28). After the second pass the level of protection can range from very low to low, depending on the size of cutblock. The level of protection could be increased by extending the period between the first and second passes, hence allowing more height growth of released spruce which would provide some sheltering effect to the strip cut in the second pass.
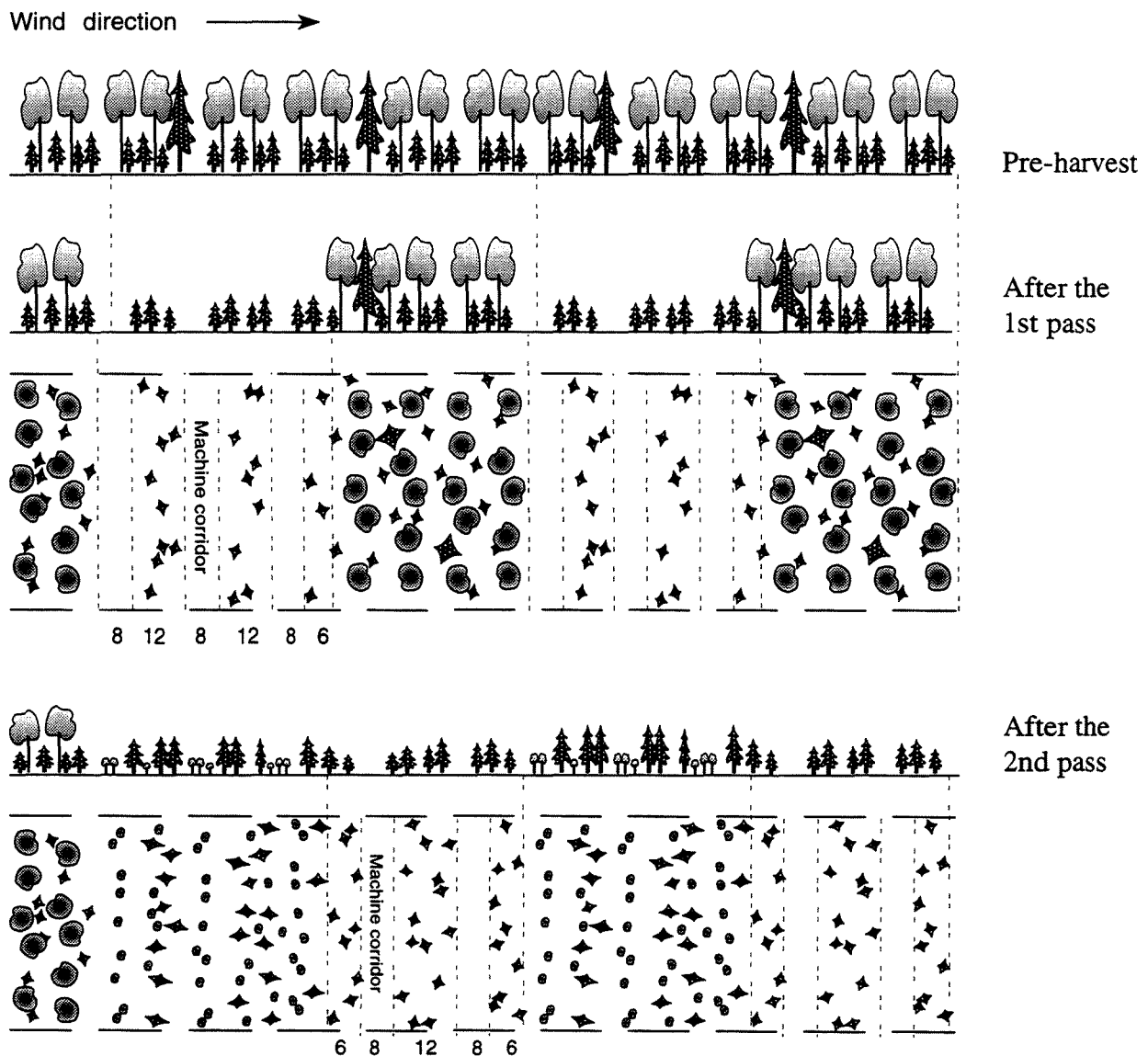

Figure 28.   Two-pass alternate strip (50m) (from Navratil et al. 1994).

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7.   Progressive strip clearcutting

Progressive strip cutting into the wind will create highly wind resistant understory stands (Figure 29). Protection during the cutting sequence is provided by the sheltering stands on the windward side. After the completion of the cutting sequence, a height gradient of spruce decreasing against the wind direction will deflect damaging winds and protect the most recently exposed strip ("A").
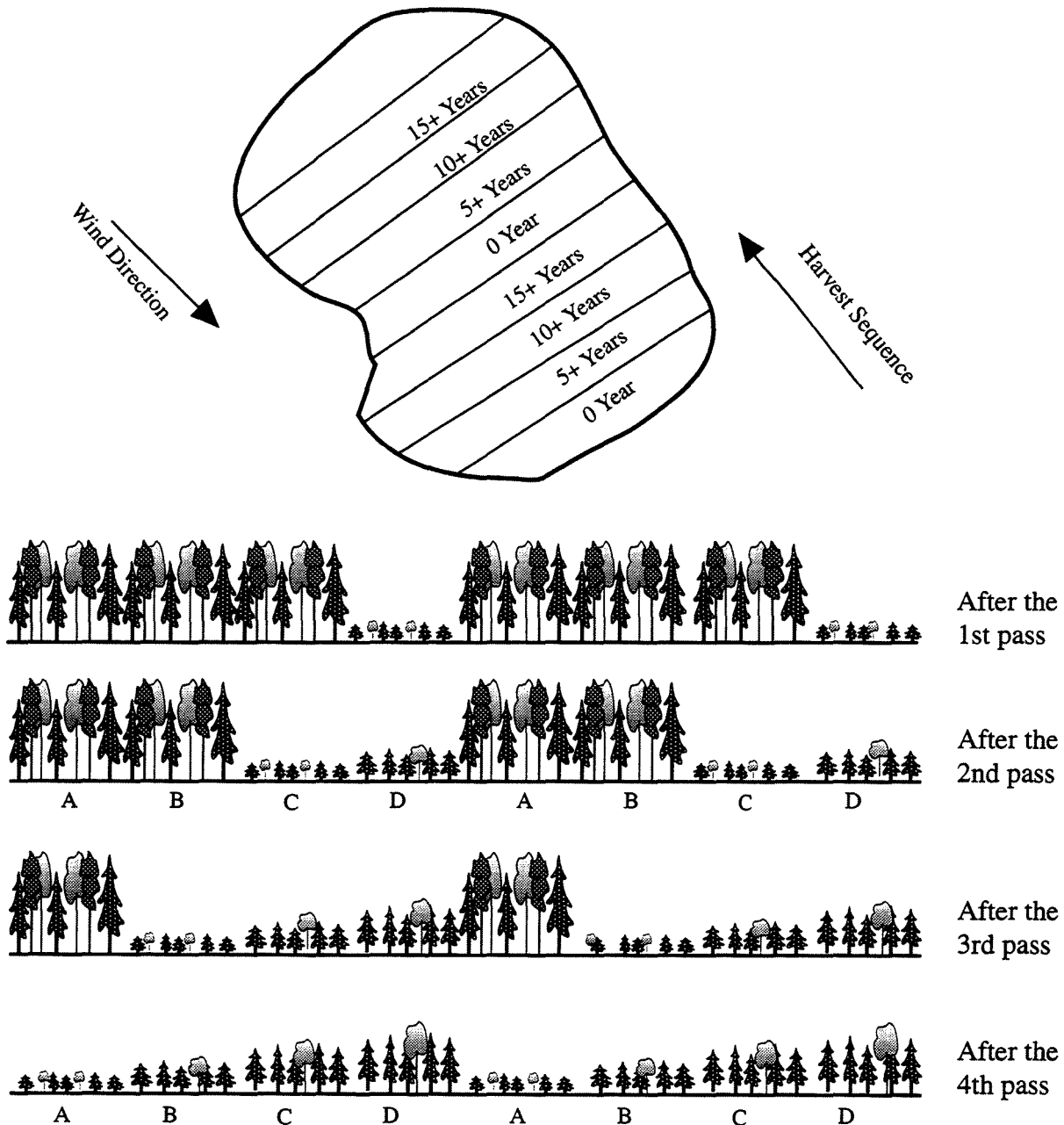

Figure 29.   Progressive strip clearcutting.

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8. Wedge strip cutting

The **wedge strip system** is a form of the progressive strip system in which cutting starts in the center strip and progressive strips are at a slight angle (Figure 30). It forms gradually widening wedges with the tips oriented toward the prevailing wind direction. The resulting height gradient of retained white spruce (or regeneration) provides a very high level of wind protection against a wide range of wind directions.
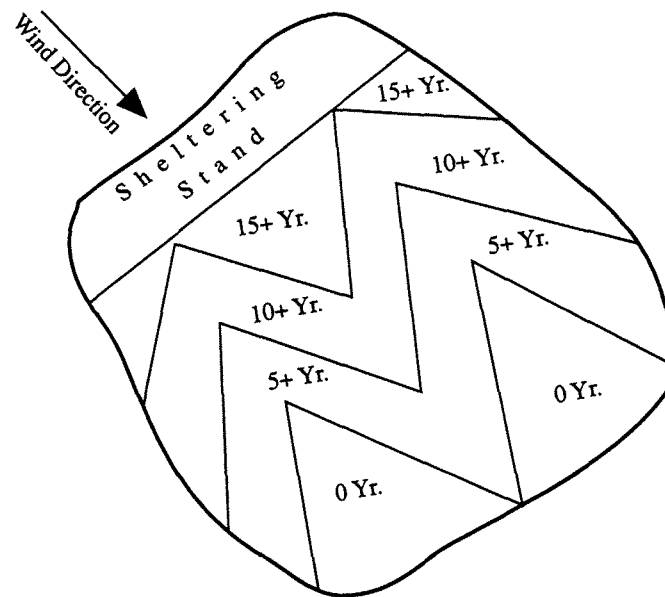
Figure 30.   Wedge strip system.

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