Windthrow Handbook

for British Columbia Forests

Research Program Working Paper 9401

Ministry of Forests
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PREFACE

Windthrow is dependent upon the interaction of a great number of factors. The importance of individual factors varies from place to place and from time to time. This handbook is intended to give users an introduction to the subject and to suggest possible options for assessing windthrow hazards and managing windthrow to minimize its impact. IT IS NOT A RULE BOOK. Users should interpret the material in this handbook in the light of their own local observations and with a good deal of common sense.

Sections 1 and 2 provide an introduction and background information about windthrow. Section 3 outlines the mechanics of windthrow. Section 4 describes the factors affecting windthrow. Section 5 outlines a method of evaluating windthrow hazard. Section 6 describes windthrow management strategies. A glossary and list of references is also included. Each section can be read independently. Users may want to skip the technical information describing the mechanics of windthrow.

To make the handbook as readable as possible, the authors have not included specific citations in the body of the text. References that apply to a specific section are noted at the end of each section. Complete citations are found in the References section. Some of the suggestions for management strategies are taken from research papers; others are based upon field observations and the authors' experiences in trying to manage windthrow.

The authors would appreciate user feedback on the usefulness and clarity of the material contained in this handbook. A questionnaire is located on a tearout page at the back of the handbook. Please take a moment to fill out the questionnaire and mail it to the address provided. User comments will enable us to expand and improve future editions of the handbook.

ACKNOWLEDGEMENTS

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1 INTRODUCTION

Windthrow is a natural phenomenon affecting forests throughout British Columbia. Every year hundreds of hectares of trees are blown over in uncut stands and along cutblock boundaries and road allowances. At recurrence intervals of 10 to 20 years, thousands of hectares of forest are windthrown by gale or hurricane force winds. This damage results in considerable loss of revenue and disrupts long-term management plans. Windthrown timber that is not salvaged can also create a fire hazard and can produce habitat conditions that increase the risk of insect epidemics. For example, the spruce bark beetle (Dendroctonus rufipennis) can very rapidly spread from windthrown trees into adjacent stands where it can cause extensive damage.

As integrated management plans for forests become more complex and diverse, the potential effects of wind damage need to be considered more carefully. The feasibility of some treatments may be questionable on certain sites because of a high windthrow hazard. Smaller opening sizes, wildlife corridors, and streamside management zones are often prone to wind damage and require careful layout and edge stabilization treatments in high hazard areas.

The Forestry Commission in the United Kingdom has developed a quantitative windthrow hazard classification scheme for identifying where wind damage is most likely to occur, however, not enough is currently known about wind zones in B.C. forests to implement a similar system. A more qualitative approach toward a windthrow hazard classification system is all that is currently possible, given that very little windspeed data has been collected in our forests and that very little is known about the threshold forces required to overturn the wide range of species and crown classes that comprise stands in B.C. Even so, a classification scheme to stratify degrees of risk of wind damage that is based upon observations, experience, and the physical principles governing the windthrow process should serve as a good starting point to develop management strategies to reduce the risk of windthrow.

2 BACKGROUND INFORMATION

From a management perspective it is useful to categorize two types of windthrow. Catastrophic windthrow occurs infrequently when exceptionally strong winds cause widespread and extensive damage to large areas. Trees are usually blown over in a single direction (within about 30° of the storm wind direction) and stem breakage is common, particularly on deep, well-drained soils where good root anchorage occurs. Endemic windthrow occurs more regularly, but on a smaller scale. It usually occurs in areas that can be recognized as having an inherently higher hazard. It occurs as a result of numerous, lower-velocity windstorms and affects individual stems or small groups of trees. Endemic windthrow often spreads progressively from an abrupt or unstable boundary and is often an indirect result of forest management practices.

It is difficult to manage for catastrophic windthrow because of the nature of storm winds, but much can be done to reduce the areal extent and damaging effects of endemic windthrow.

Different types of wind damage have been recognized. These include: 1) stem break, where the bole of the tree snaps well above the ground, 2) stock break, where the bole snaps at ground level, 3) root break, (a rotational fall) where the tree is uprooted by pivoting on broken roots directly beneath the bole; and 4) tree throw, (a hinge fall) where the tree is uprooted by pivoting on the outer edge of a massive plate comprised of soil and roots. Similar forces are required to break or uproot trees and often both types of damage occur within a stand during a storm.

Stem break has been noted to occur more frequently during strong gales and hurricane force winds, particularly on sites where good root anchorage occurs (i.e. where the anchorage strength exceeds the turning force and the bole strength), and in trees that have been structurally weakened by disease. Trees with large height-to-diameter ratios, large crowns, and high crowns also tend to snap off rather than overturn.

Rotational falls usually occur after the main supporting bracket roots are progressively broken during a storm. They typically occur in trees with relatively small root systems, trees with root rot, or trees growing in sandy or wet soils that have low shear strength. Hinge falls occur more commonly in trees with a shallow, plate-like root system on very wet sites, or on shallow soils.

Windfirmness is the ability of a tree to resist overturning. It is a function of the balance between the anchorage or strength of the root/soil mass and the wind drag and gravitational forces applied on the tree crown. Other terms relevant to windthrow are defined in the glossary.

Suggested Reading

Catastrophic versus endemic windthrow: Alexander (1964, 1986), Somerville (1980), Holmes (1985), Busby (1965), Cremer et al. (1982)

Effects of disease: Hubert (1918)

Types of wind damage: Mayer (1987), Shaetzl et al. (1989), Cremer et al. (1982)

Windthrow hazard classification: Miller (1985)

3 MECHANICS OF WINDTHROW

Though it might initially appear that the process by which wind blows a tree over is very simple, a wide range of forces can actually cause windthrow. The mechanics of the process are complex and dynamic, and many interacting factors can be involved. It is useful to examine the mechanics of the windthrow process for a single tree to understand the role of various factors.

Windthrow occurs when the horizontal forces on a tree are transmitted down the trunk to create a torque that exceeds the resistance to turning of the root/soil system. The torque, or turning moment, at the base of the tree can be estimated by dividing the tree into height increments and summing the contribution of the torque from each height interval as follows:

$$\text{Torque} = \Sigma(F_i h_i) \quad (1)$$

where h_i is the height of the i-th increment and F_i is the horizontal force on that increment. As trees grow taller they can become increasingly prone to windthrow. For example, a force of 100 N applied at a height of I0 m creates a torque of 1000 Nm, but the same force at the 30 m height generates three times as much torque.

Two horizontal forces contribute to the torque at each height increment. The first force is a function of the effect of wind on the crown at height i as follows:

$$F_i = \rho \, A_i \, C_{Di} \, u_i^2 \; / \, 2 \quad (2)$$

where ρ is the density of air, A_i is the projected area of the crown perpendicular to the direction of the wind, C_{Di} is the drag coefficient of the crown, and u_i is the wind speed at height i above the ground. The second force is a gravitational force that is contributed as the tree sways away from the vertical axis as follows:

$$F_i = m_i \, x_i \, g \quad (3)$$

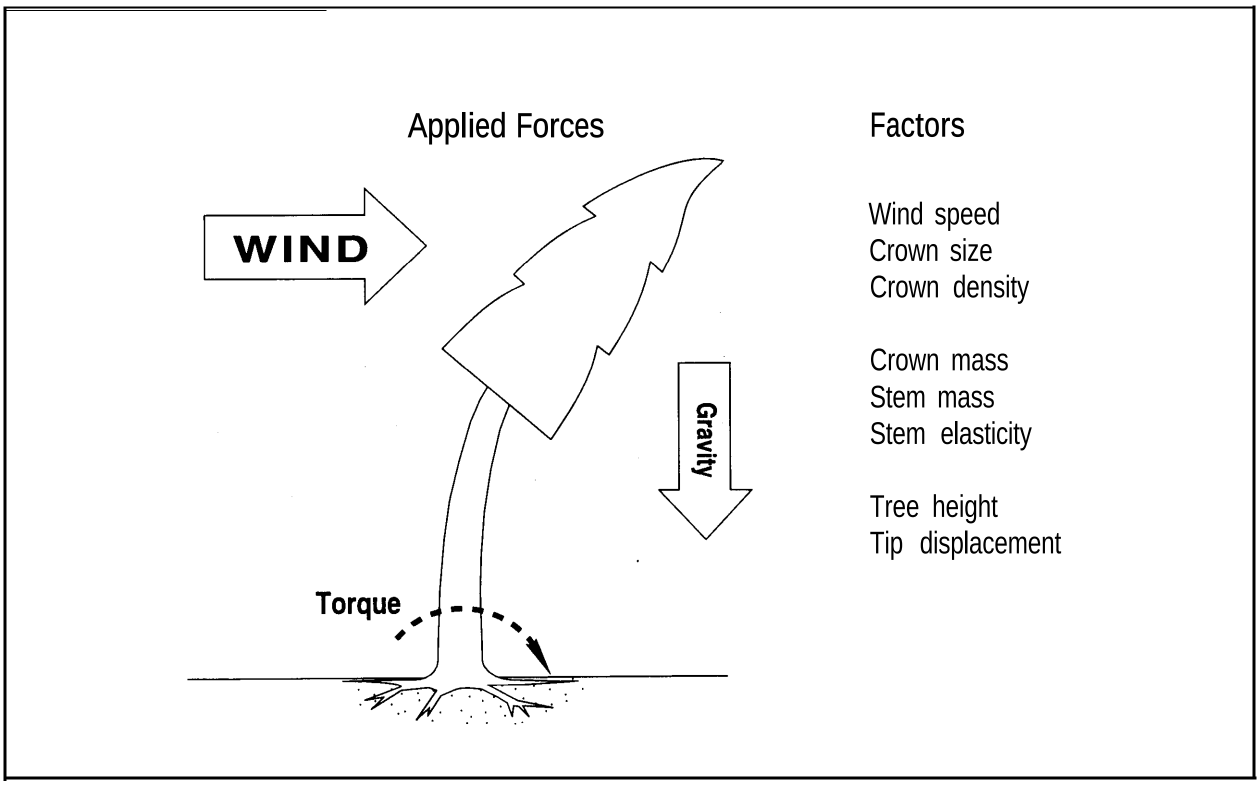

FIGURE 1. Factors affecting wind and gravitational forces acting on a tree.

where m_i is the mass of the height increment, x_i is the horizontal displacement from the vertical, and g is gravitational acceleration. The gravitational force is relatively weak compared with the force of the wind on the crown until the tree starts to sway well away from the vertical axis. At a sway angle of 15-20°, the gravitational force can become a considerable proportion of the total horizontal force.

The drag force on the crown is proportional to the area of branches and stems exposed to the wind, the drag coefficient of the foliage (i.e. how efficiently it intercepts wind), and the square of the wind speed (i.e. when the wind speed doubles, the drag force on the crown increases by a factor of four). Wind tunnel studies with whole trees have shown that the drag force is nearly proportional to the projected area of the canopy, drag coefficient, and wind speed. However, as wind speed increases, the canopy tends to bend and deflect and become more streamlined.

Drag coefficients have been found to vary considerably between species. Engelmann spruce and subalpine fir have stiff branches and needles and relatively high drag coefficients (~0.5-0.8) compared to the more flexible branches of lodgepole pine and Douglas-fir (0.3-0.6), or the very spindly branches and crowns of western hemlock (0.2-0.3). [Drag coefficients at wind speeds of 25 m/s and 10 m/s, respectively.] Taller individual trees growing within forest canopies that have uneven height or density distributions intercept more wind and therefore require stronger root anchorage to counter the increased drag force. The drag force of the wind on the crown results in branch and needle deflection. This force is transmitted to the stem, causing it to bend and sway. The sway period and amplitude are functions of the height, stiffness, and shape of the stem, the stiffness of the anchorage of the root system, the effect of adjacent tree crowns on motion damping and turbulence, and the speed and turbulence characteristics (gustiness) of the wind within and over the canopy. The presence of trees of varying heights and gaps or openings within a canopy act to increase atmospheric turbulence; however, relatively little is known about the effect of opening size or canopy architecture on the downstream wind field.

Studies of the relationship between the sway period and amplitude, damping, and structure of the wind turbulence have found that large eddies can contribute significantly to the shear stress on individual

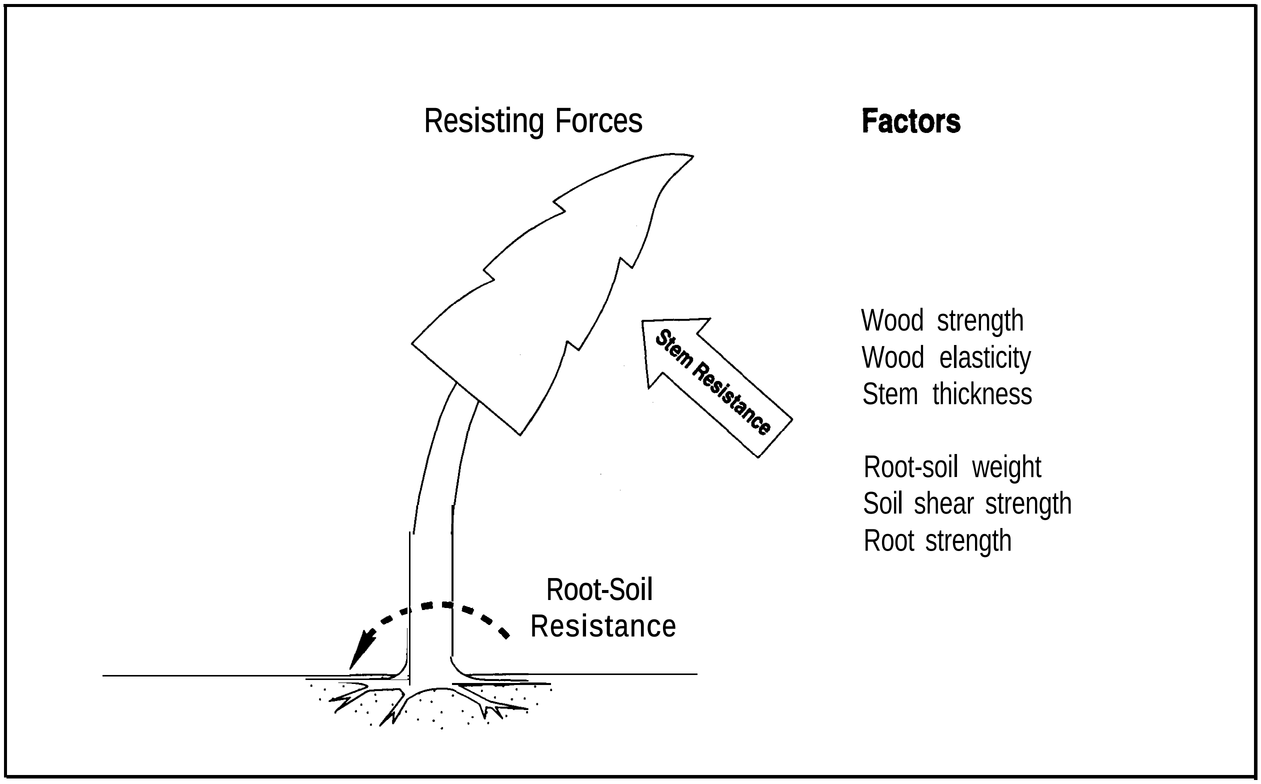

FIGURE 2. Factors affecting the resistance to wind and gravitational forces acting on a tree.

trees. When wind acceleration resulting from turbulence is in phase with the natural sway frequency of a tree, the amplitude of the sway can be increased considerably. Hence, even during relatively low wind speeds, a certain frequency of gusts (or eddy sizes) can transfer energy to a swaying crown that causes it to increase in amplitude over a period of a few sways until it reaches a threshold turning moment. The sway period of trees varies from about 3-6 seconds. Tall, slender, cylindrical stems sway more than short, conical stems. Damping of the swaying motion by contact with adjacent crowns can provide considerable force dissipation by spreading the force over many stems. Dense, even-aged lodgepole pine stands are often prone to windthrow and stem break after partial cutting because of their bole characteristics and the loss of damping through contact with adjacent crowns.

The drag force on a tree crown is counteracted by a number of resistances. As the wind speed increases, the main stem, branches, and needles are deflected by the wind such that the tree becomes more streamlined. As a result, the projected area of the canopy decreases and the drag coefficient decreases. Swaying of the bole also dissipates energy. The amount of deflection of the bole is dependent on its diameter, elasticity, and shape. A conical trunk is considerably stronger than a cylindrical trunk (in which strength is a function of the cube of the bole diameter/height). Older trees and open-grown trees usually have more taper than trees in even-aged, uniform canopies.

Relatively little is known about the threshold turning moments for the range of crown classes, heights, and stand densities for different species. The static turning moments of 10 m tall Sitka spruce trees were found to range from 3-14 kN m* ,and were well correlated with height and diameter. Threshold static turning moments

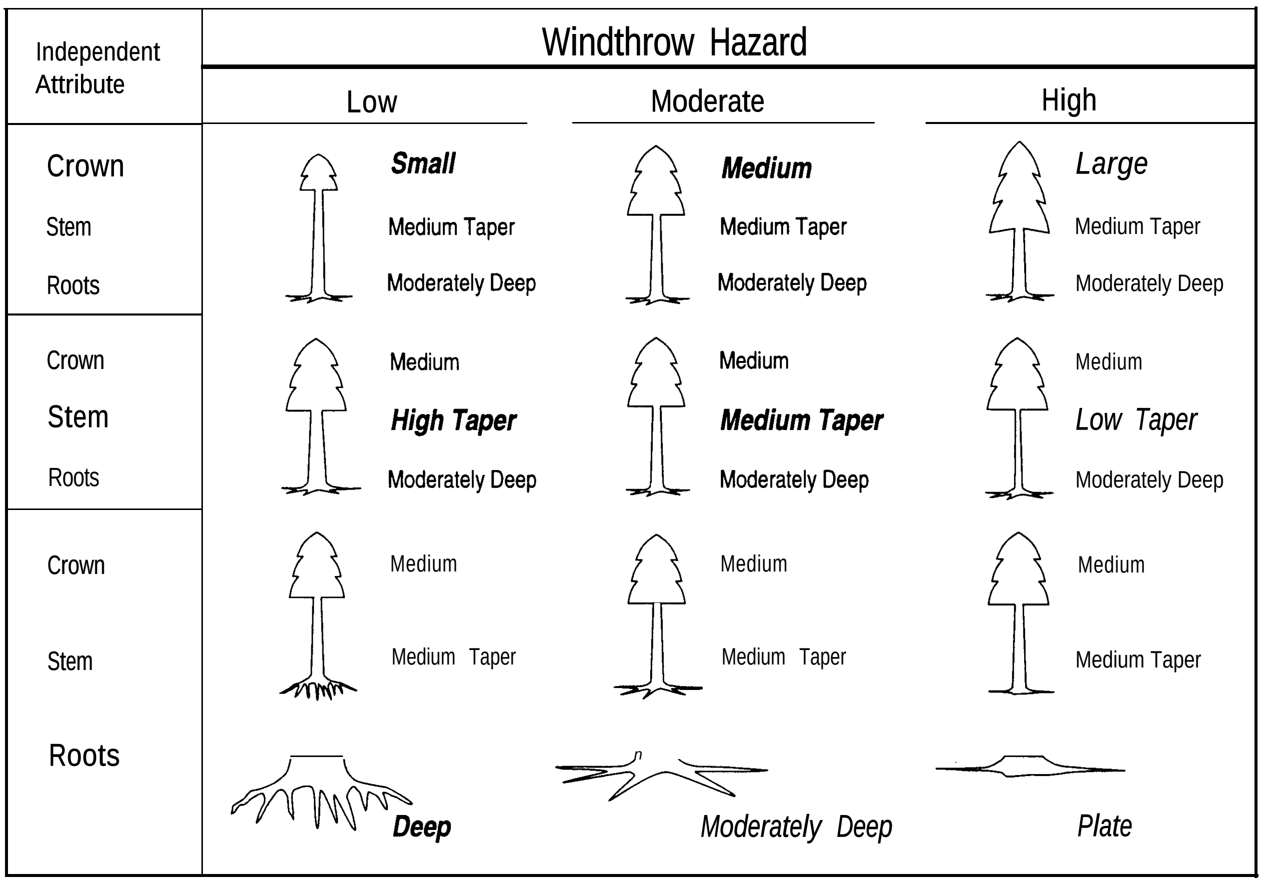

FIGURE 3. Crown, stem, and root attributes that affect the risk of windthrow.

* Units of torque are in kN m: kilo Newton metres. A force of 1 Newton metre is generated by applying a mass of 1 kg at a distance of 1 metre on a cantilever.

of 18-21 m tall Sitka spruce varied from to 9-33 kN m. Threshold turning moments in black spruce have been found to be well correlated with height and stocking density, with values ranging from about 5 kN m in 15 m tall stands to 14-l 8 kN m in 22 m tall stands. The turning moments required for uprooting and stem breaking have been found to be of similar magnitude. Turning moments are likely to be quite variable in old-growth stands because of the variability in species, canopy characteristics, ages, heights, densities, and rooting habits.

The characteristics of root systems, the factors affecting anchoring strength, and the dynamics of root shearing as a result of static and dynamic wind action on the canopy have been examined by several researchers. Most of this work pertains to Sitka spruce and Douglas-fir; however, it also applies generally to other species. These studies have shown that the physical properties of the soil that govern root morphology and the overall size of root/soil mass are the most important determinants of the strength of anchorage. Small increases in rooting depth and area can significantly increase the resistance to overturning.

During a storm, tree crowns sway back and forth with elliptical motion, the major axis of swaying in the direction of the wind. This motion continually applies tensile, compressive, and shearing stresses to all sides of the root system. Tree roots are about three times stronger under tension parallel to the grain than they are under compression in the same direction. Hence, the first root shearing usually occurs in small diameter roots on the leeward side of the tree as a result of compressive forces from forward sways. The loss of strength on the leeward side then allows a greater backsway and causes roots on the windward side to fail under compressive stress. On plate-like root systems, the resistance to pulling of the large lateral roots on the windward side of the tree contributes the most anchorage strength.

The pumping action of the root plates of large swaying trees is likely to cause progressive weakening of the soil-root system. Continual swaying during a storm progressively shears and weakens roots or abrades them if they are adjacent to rocks. When examining windthrown trees, it is often possible to see

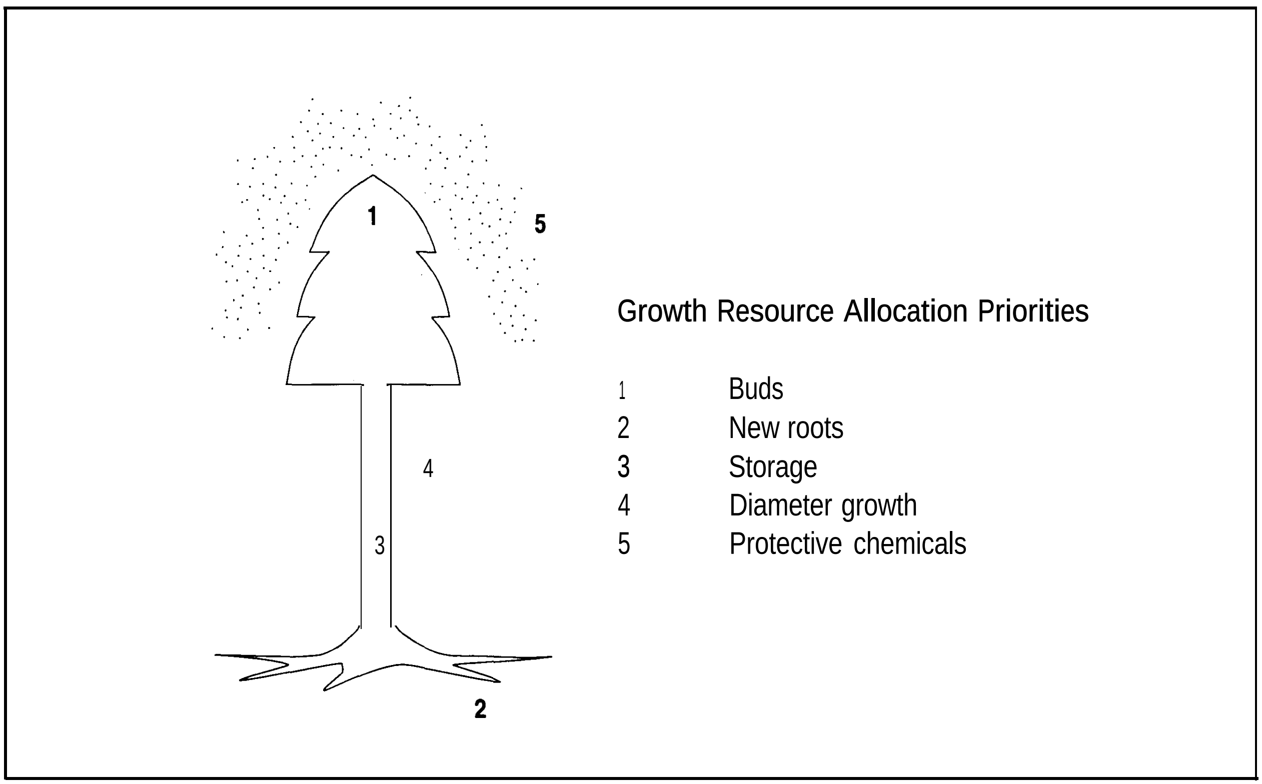

FIGURE 4. The normal hierarchy of growth resource allocation where production of foliage and fine roots takes precedence over stem and root diameter increment. (Source: After Waring and Schlesinger, 1985.)

where roots have been broken and abraded in previous storms and have subsequently callused over and healed. Longer duration storms of lower intensity or more frequent low intensity storms can sometimes cause windthrow by progressively weakening the soil/root system, especially if the soil is wet.

Major lateral roots (>0.5 cm diameter) largely determine the resistance to overturning. The stiffness of a root is proportional to the fourth power of its diameter; hence when a root forks into two equal branches, its stiffness is halved. Therefore, root systems comprised of large roots are stronger and provide more resistance to swaying than those with a great number of smaller roots. The force required to extract roots increases as a function of their diameter and length. Increased anchorage strength also results from the intermingling of root systems with adjacent trees. Stability may be quite sensitive to rooting symmetry, especially when rooting is restricted.

Windfirmness changes slowly as trees grow in response to their environment. To remain windfirm as they grow taller, stems and structural roots must be thickened in proportion to the additional wind and gravitational forces that must be withstood. In the normal hierarchy of growth (outlined in Figure 4), production of foliage and fine roots takes precedence over thickening of the stem and structural roots. Trees that grow in dense stands have relatively low individual windfirmness because the production of crown and fine roots uses most of the available growth resources. In contrast, trees that grow at a wide spacing are more windfirm because they develop larger root systems and thicker, tapered stems. The stimulus for additional thickening of structural tissues is wind-induced swaying. Specialized reaction wood may also be formed if stems are tilted or bent.

Windthrow management involves the use of treatments which modify root anchorage strength and wind force on the canopy.

Suggested Reading

Mechanics of windthrow: Petty and Swain (1985), Blackburn et al. (1988), Cremer et al. (1982), Mayer (1987), Oliver and Mayhead (1973), Fraser (1964)

Tree and stand effects: Fraser (1964), Mayhead (1973), Mayer (1987) Mayer (1989), Holbo et al. (1980), Coutts (1986), Smith et al. (1987)

Root system effects: Fraser (1962), Fraser and Gardiner (1967), Coutts (1983), Mergen (1954), Anderson et al. (1989), Day (1950)

Wind and tree growth: Jacobs (1954), Larson (1965), Mattheck (1991), Robertson (1987)

4 FACTORS AFFECTING WINDTHROW

The factors that affect windthrow are those that influence the effectiveness of root anchorage, the strength and aerodynamic properties of the tree, and the direction and characteristics of the wind within and above the stand. For simplicity these can be separated into individual tree characteristics, stand characteristics, root zone soil characteristics, topographic exposure characteristics, and meteorological conditions.

4.1 **Individual Tree Characteristics**

At the individual tree level, the following characteristics affect tree stability:

+ the height, diameter, and shape of the bole
+ the crown class and size of crown
+ the strength and elasticity of the bole, branches, and needles
+ the rooting depth and area, size and number of roots, and whether or not adjacent tree root systems interlock.

Members of a stand can have widely differing susceptibilities to windthrow because of variations in these characteristics.

Research results linking species to windthrow have been somewhat contradictory because of the interacting effects of site and stand characteristics on tree form. Many of these characteristics vary between species and so certain species may appear more windfirm than others. For example, on wet sites Western redcedar is considered to be more windfirm than hemlock and balsam fir because of its crown characteristics and rooting habits. Ponderosa pine is usually very windfirm because of its open-grown nature; however, Douglas-fir is also very windfirm on dry sites. On high-elevation sites lodgepole pine and Engelmann spruce often appear more windfirm than subalpine fir; however, their windfirmness may be more a function of site-specific conditions, age, or disease. Sound snags of any species that lack a crown to act as a sail are typically less vulnerable to windthrow than live trees. Species alone should not be considered a very reliable predictor of windthrow susceptibility.

Trees with large or medium dense crowns are more vulnerable to windthrow than trees with smaller, open crowns. Crown modification techniques such as pruning and topping to reduce the effective crown size and density can considerably reduce the risk of windthrow. Taller trees are also generally more prone to windthrow because of their greater potential turning moment. However, tall trees can be quite windfirm if they have been exposed to wind and are well rooted in deep, freely draining soil.

Many studies have indicated that the incidence of windthrow is increased in trees that have poor root anchorage resulting from saturated soils, soils with restricted rooting depths, or where root morphology is affected by treatments such as trenching or mounding.

Root and bole rots have been found to be associated with high frequencies of both windthrow and stembreak, because of their effects on root anchorage and bole strength. Surveys of windthrow in high-elevation Engelmann spruce-subalpine fir forests in the U.S. Rocky Mountains have found root or bole rots associated with about one-third of the wind damage. Other studies have shown that 20-50% of wind-damaged trees have evidence of infection by various types of rot.

Stem taper may be an important factor affecting susceptibility to stem breakage. The height-to-diameter ratio of dominant trees in even-aged stands has been found to be a good indicator of risk of stem breakage. Stem breakage is less likely in stands where trees have height-to-diameter ratios of less than 60. When the height-to-diameter ratio of a tree exceeds 100, it is more prone to windthrow and stem breakage.

Crown class alone is not a reliable predictor of windthrow hazard. There is some evidence to suggest that dominant, codominant, and veteran trees are less susceptible to windthrow than the intermediate and suppressed crown classes if they have been exposed to wind for a long time. Older trees often have a higher windthrow hazard because they are typically taller, have greater stem-to-root ratios, and are more likely to have root diseases.

4.2 **Stand Level Characteristics**

At the *stand level,* individual trees can be made more or less prone to windthrow through the effects of:

+ stand height and density
+ species composition
+ silvicultural treatments (thinning, pruning, edge feathering, ripping, draining, etc.).

Stand height and density affect wind flow and hence the drag force on individual trees. Dense stands are usually quite windfirm because of interlocking root systems, inter-tree crown damping during swaying, and the effect of the dense crowns on reducing wind penetration into the stand. The individual trees that make up a dense stand are often not windfirm in isolation because of restricted rooting as a result of competition and a high height-to-diameter ratio. These stands can be very prone to windthrow after thinning. Studies of model forests in wind tunnels have indicated that the drag force per tree can increase by up to 40% when the tree spacing increases from 25% of tree height to 40% of tree height.

Younger stands are typically more windfirm than older stands. Old-growth stands can have a high incidence of root and butt rots which can make them more susceptible to wind damage. Older dominant trees and veteran trees can be very windfirm, particularly if they are deeply rooted and have been exposed to wind for a long time. Because of their greater exposure to wind, individual trees in thrifty, uneven-storied stands also tend to be more windfirm than canopies with a more uniform height. Some European research suggests that mixed deciduous and conifer stands may also be more windfirm.

Wind damage usually occurs in the first few years after harvesting, particularly where more susceptible trees are exposed to stronger winds as a result of harvesting. Trees can become more windfirm after a few years of exposure as they develop reaction wood in response to swaying. This response may take longer in high-elevation stands because of the slow growth rates resulting from the short growing season and harsh environmental conditions.

Certain operational treatments can increase the windthrow hazard by increasing the wind speed and turbulence. Clearcuts can create problems in this respect. Windthrow usually occurs on the downwind edge of cutblocks and can extend into the stand for hundreds of meters, although most damage is usually concentrated within the first 10-20 m of the cutting boundary. Less wind damage usually occurs on upwind boundaries and along boundaries parallel to storm wind directions. Opening size does not seem to have a significant effect on the amount of windthrow. However, as opening size increases there may be more opportunity to find windfirm boundary locations. In some areas, very small openings (<1 ha) have proven to be relatively windfirm.

Wind tunnel experiments with model forests have shown that the force on the downwind edge of a clearcut is dissipated within a short distance into the stand, but that turbulence resulting from accelerated wind flow over the edge of the stand causes zones of very high turbulence a few tree heights downwind until the flow is reattached to the canopy. This turbulence increases the risk of windthrow in this zone.

Thinning can significantly increase wind damage, particularly in dense, even-aged stands. Except for sites where root growth is restricted, plantations raised at lower stocking densities generally experience much less wind damage. Extensive damage can occur in stands that are heavily thinned, especially if dominants are removed and if the residual trees are tall and slender. A number of studies have shown that less wind damage occurs after low intensity thinnings (>25% of stand volume), while severe damage can occur in stands where the dominant trees have been removed.

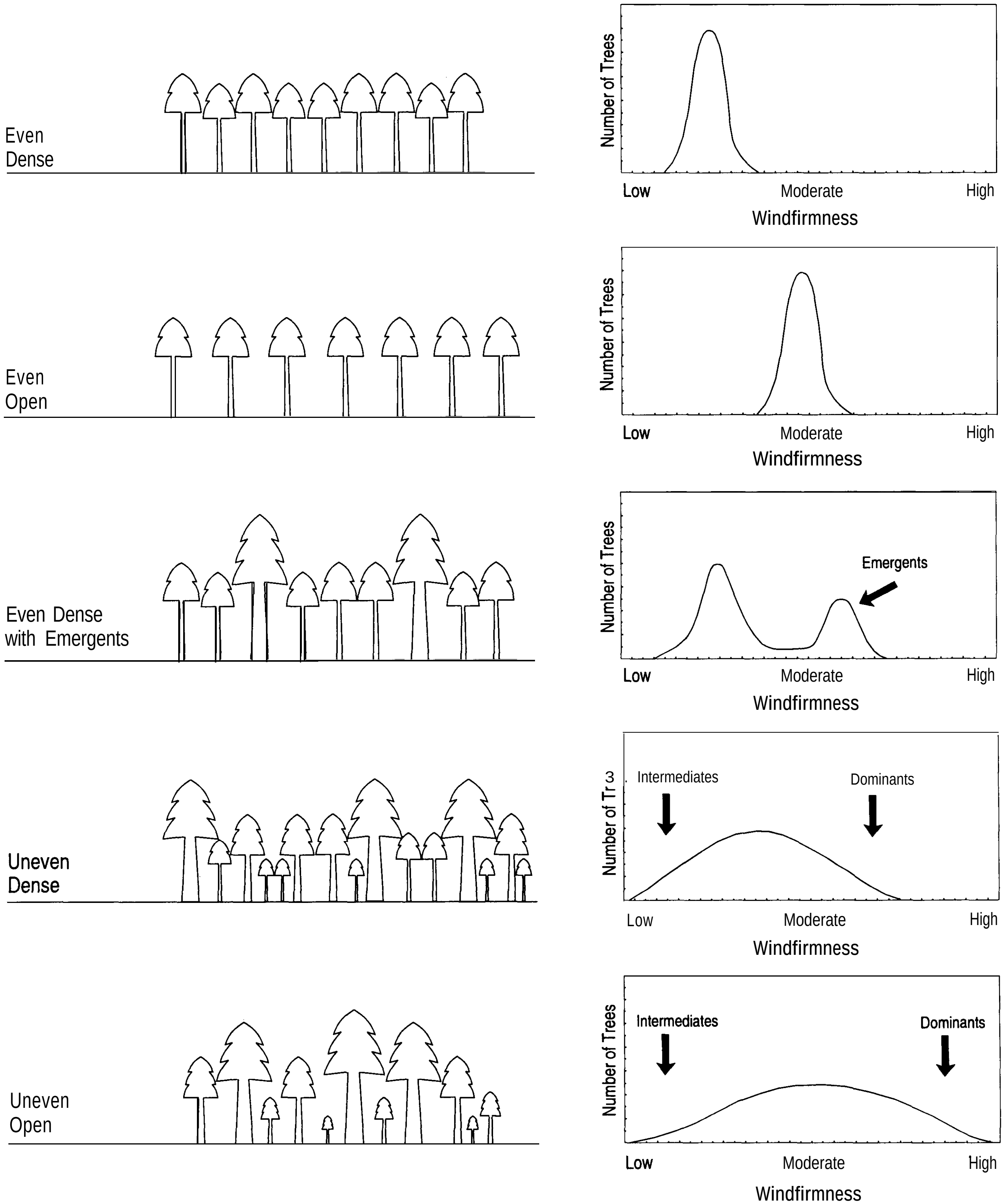

FIGURE 5. A comparison of distributions of the relative windfirmness of individual trees comprising stands with different structural characteristics.

Pruning in young stands should reduce windthrow by reducing the crown area exposure and hence the turning moment on the stem. However, some studies have shown mixed results, possibly because opening the canopy also increases the wind speed and turbulence within the canopy.

4.3 **Soil Characteristics**

Soil characteristics affect windthrow through the interaction of:

+ depth
+ drainage
+ structure, density, texture, and stoniness on the anchorage strength of the root system.

Trees growing in deep, well-drained soils produce much larger root systems than those in soils where saturated conditions, high bulk density, stoniness, pans, or near-surface bedrock restrict root development. Typically, trees growing on deep, well-drained soils are much more windfirm than those growing on shallow or poorly drained soils. Trees growing in conditions where rooting is confined to the organic layer are often quite vulnerable to windthrow.

On shallow or very wet soils roots usually form a plate-like structure up to 4 m in diameter and often less than 0.4 m deep. This plate forms a foundation for the tree that provides adequate stability when the tree crown is protected from high winds within a canopy, but often does not provide enough anchorage strength if the adjacent canopy is removed.

Soils, particularly when wet, have shear strengths that are two to three orders of magnitude less than roots; hence adhesion and cohesion of the soil to individual roots plays a relatively small role in supporting the tree. Soil conditions appear to play a greater role in anchorage strength by affecting the total volume of the root system and the size of individual support roots.

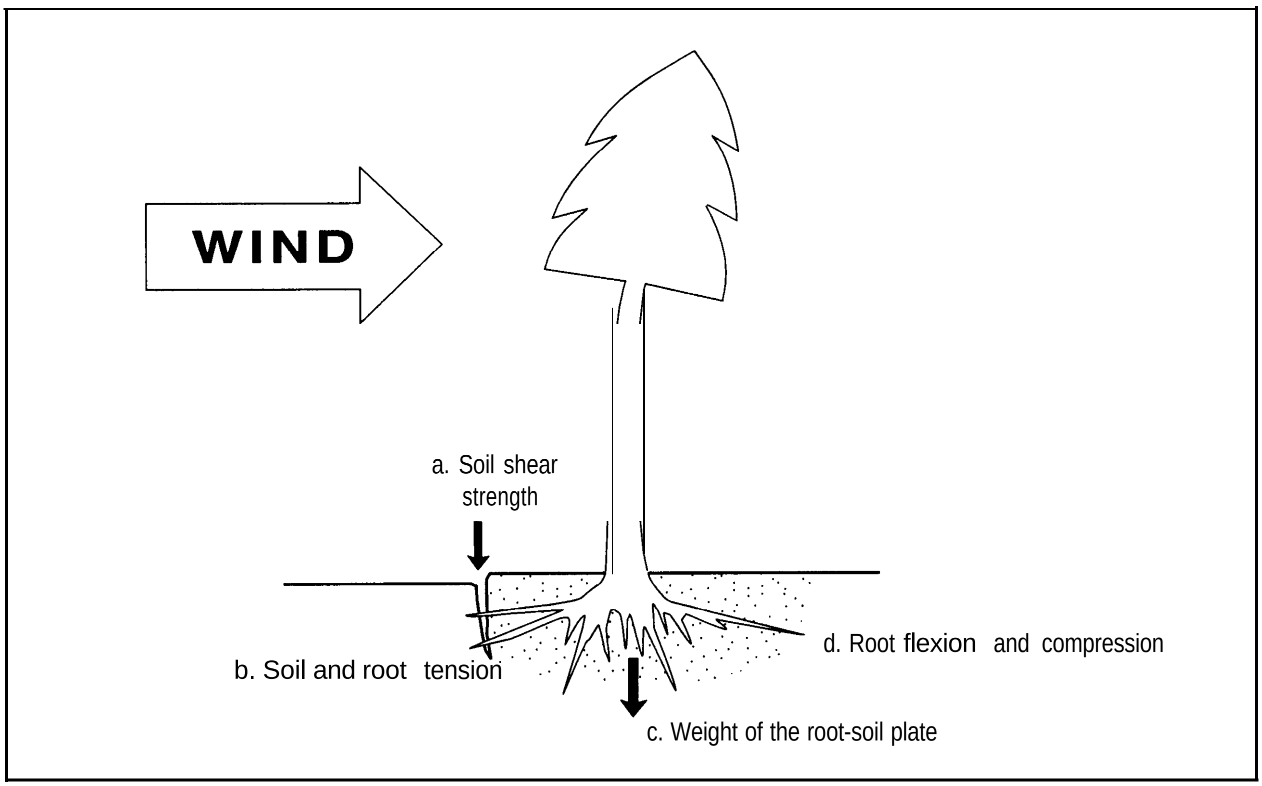

FIGURE 6. Root and soil factors affecting resistance to overturning. (Source: After Ruel, 1992.)

There appears to be a consensus in most windthrow studies that the *soil factors that control rooting depth contribute most significantly to the risk of windthrow.* Shallow rooting is most likely to occur on shallow soils overlying bedrock (e.g. Follisols) and on poorly drained sites where root growth is restricted by a high or fluctuating water table. Deeper rooting, and hence greater resistance to overturning, is more likely to occur on deep, well-drained Podzols and Brunisols than on organic soils or Gleysols. Luvisolic soils often have very dense (>1.6 Mg/m3), clay-rich horizons that can restrict rooting depths.

4.4 **Topographic Characteristics**

Topographic characteristics affect windthrow by modifying:

+ wind exposure
+ wind direction, speed and turbulence.

The effects of terrain on wind flow are complex, however, it is possible to characterize certain landforms where the inherent risk of windthrow is higher because of wind acceleration or increased turbulence. The speed and direction of the wind at a height of about 1000 m above the surface is largely governed by the atmospheric pressure gradient and rotation of the earth. Nearer the surface, this flow becomes increasingly turbulent as the frictional drag of surface features plays a greater role. Surface winds flow over and around hills and can change direction by up to 90° as they are funneled through valleys and around mountains. As wind streamlines are compressed by flowing through narrowing valleys, over hills and ridges, or around shoulders, the wind velocity increases. In the lee of mountain ridges or even relatively small hills (~30 m above surrounding terrain), a turbulent wake develops rotor eddies that can have strong vertical velocities. This type of high-velocity turbulent flow is often responsible for wind damage on lee slopes. Areas of high topographic susceptibility to windthrow are summarized as follows:

Rounded Hills: The flanks, particularly sloped terraces, lateral lower and middle slopes, and the lower lee side slopes are more susceptible because of increased velocity and turbulence. There is also high susceptibility on the leeward side of a rounded hill, especially where the relief rises again behind the hill.

Mountain Ridges: When wind flow is parallel to the slope, the speed and turbulence are highest near the lower slopes. When wind is at an oblique angle to the slope (20-50°), the flow becomes turbulent at mid-slope and often changes direction. When the flow is perpendicular to the slope, the velocity increases from the lower to the upper slopes and the speed is highest at the summit. Immediately behind the summit, wind velocity abates, but lee waves create high turbulence where the mixing zone reattaches to the surface relief. The most susceptible areas behind steep leeward slopes may be over sloping leeward terraces, over the plain immediately behind the leeward slope of the ridge, or over the windward slope of the next hill.

Valley Bottoms: When wind flows along or up a valley, the streamlines are condensed and the flow velocity increases near the valley bottom. Narrow valleys cause wind speeds to increase (much like a venturi) more than wide valleys do, particularly if they become increasingly narrow and rise in elevation. Valleys incised into a plateau can also be particularly windy if oriented in the direction of the wind.

Shoulders: Secondary ridges that protrude at right angles act in a similar manner to rounded hills. The upper windward slopes, crest, and lee slopes exhibit the highest wind speeds and turbulence and hence are at greatest risk.

Saddles: Saddles act as narrow valleys that compress the wind streamlines and cause the wind to accelerate considerably. These topographic features appear to affect wind flow over a wide range of scales. The valley bottoms in high-elevation passes are prone to windthrow. The lee slopes of steep ridges are also at higher risk. Windthrow hazard is often higher on moderate to steep slopes than on flat terrain or gentle slopes, although there is mixed evidence for this observation. Often there are confounding influences of poor root anchorage and wind in certain topographic positions, and it is hard to discern which factor contributes more to the windthrow hazard (e.g. wet sites in valley bottoms, or shallow soils on ridge crests). The orientation of a cutting boundary can have a greater effect on windthrow hazard than the lee or windward character of a particular slope.

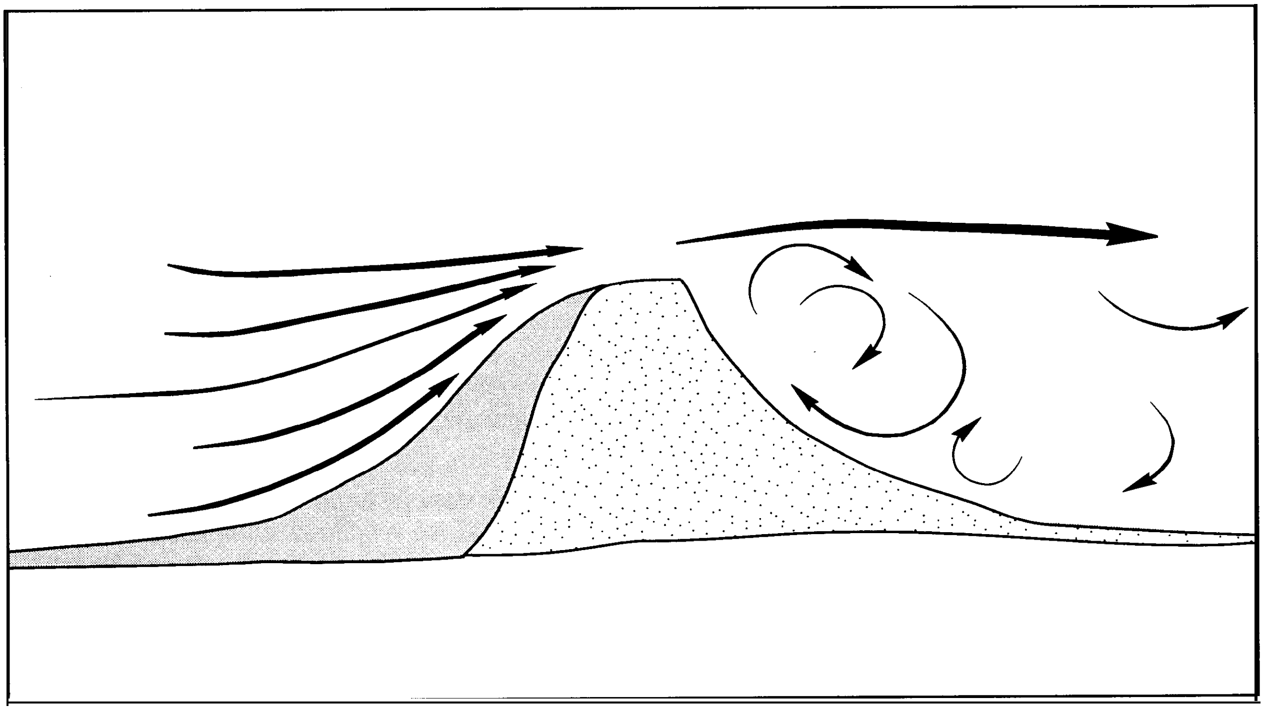

FIGURE 7. Wind flow over a hill showing flow acceleration on the windward slope and turbulence (roller eddies) on the leeward slope. (Source: After Ruel, 1992.)

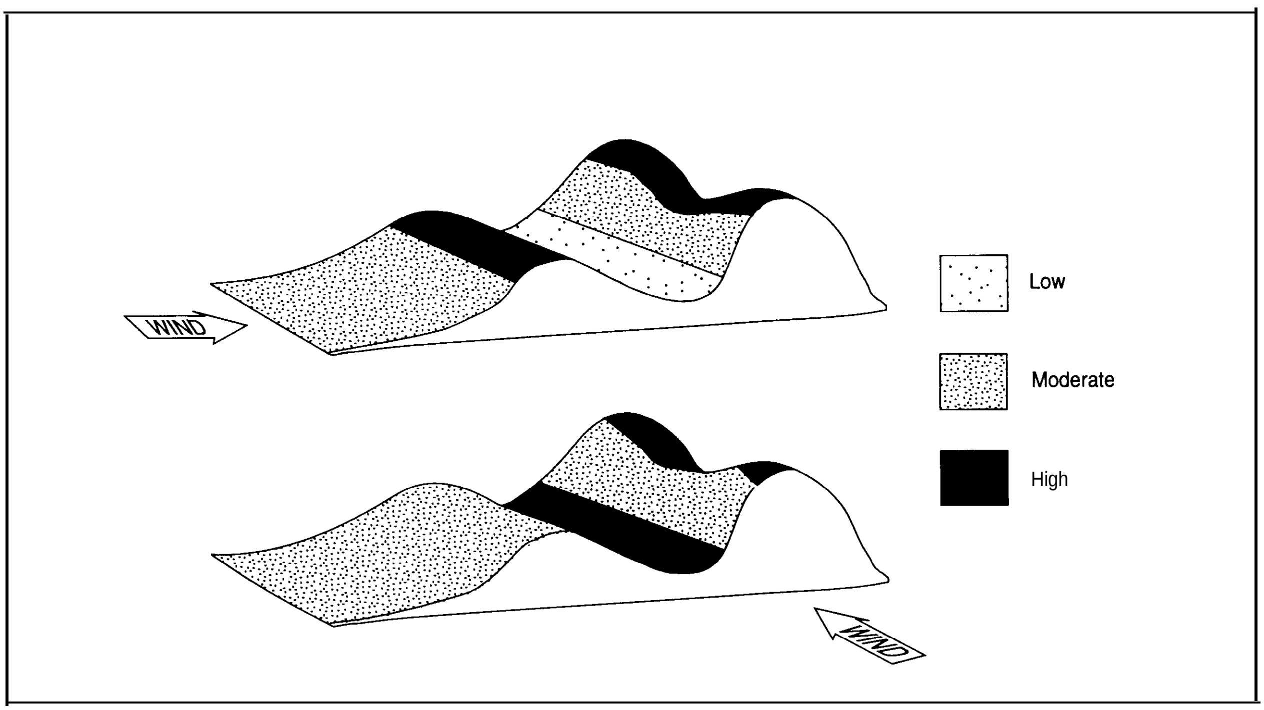

FIGURE 8. The effects of topography on wind speed. When the wind direction is perpendicular to a ridge the wind speed is relatively low in the valley bottom and increases to a maximum at the ridge top. When the wind direction is parallel to a ridge higher wind speeds occur in the bottom of the valley and near the ridge crest. (Source: After Alexander, 1987.)

4.5 Meteorological Conditions

Meteorological conditions affect windthrow through the effects of:

+ wind speed, gustiness, and storm duration
+ soil moisture conditions
+ snow and rain loading on the crown.

Few trees are strong enough to withstand mean wind speeds in excess of 30 m/s (~100 km/hr) for more than about 10 minutes, yet considerable windthrow can occur in some stands at wind speeds of only about 15-l7 m/s (~50-60 km/hr). Prolonged storms allow more time for a swaying bole to break roots and loosen root anchorage. Windthrow is often more severe during storms when the soil has been wet by previous heavy rainfalls because of the resultant reduction in root-to-soil adhesion and soil shear strength. Snow or ice loading on the crown can also increase windthrow susceptibility through the effects of increased canopy mass and an increase in the drag coefficient.

Complex terrain and surface drag resulting from a heterogeneous canopy or openings in the canopy can induce considerable turbulence in the wind flow. Wind gusts that cause windthrow often occur in bands that range from I0-250 m wide. They occur repeatedly during storms lasting several hours and have speeds ranging up to 50% higher than the mean wind flow at the surface. Gusts at the surface can have speeds comparable to that of the bulk flow 1000 m higher.

In British Columbia, most of the strong winds that cause windthrow are associated with the passage of fronts that originate in the Pacific Ocean or in the Arctic. Gale-force winds occur regularly during the winter, spring, and fall. Hurricane-force winds are not uncommon in more exposed locations. Strong winds associated with thunderstorm activity can also cause windthrow during the summer.

The strongest winds typically blow in a southeast or northwest direction on the coast. In the interior regions strong winds occur more commonly from the north, south, and west than from the east. Local terrain plays a considerable role in modifying the wind direction and speed in the interior, particularly in mountainous regions. The wind direction can shift by up to 90° as wind is funneled through a valley. Areas where two or more valleys converge can be more difficult to manage because they can experience strong winds from both valleys.

Suggested Reading

Individual tree factors **:** Alexander (1964), Blackburn (1983), Cremer et al. (1982), Hubert (1918), Hutte (1968), Petty and Swain (1985) Smith and Weitknecht (1915).

Stand factors: Alexander (1964), Blackburn et al. (1988), Cremer et al. (1982), Fraser (1964), Smith et al. (1987), Somerville (1980), Ruth and Yoder (1953), Harris (1989).

Soil factors: Alexander (1964), Kennedy (1974).

Topographic factors: Alexander (1964), Gloyne (1968), Hutte (1968).

Meteorological factors: Day (1950), Fraser (1964), Gloyne (1968), Mayer (1987), Oliver and Mayhead (1974).

5 WINDTHROW HAZARD EVALUATION

A quantitative approach to determining the windthrow hazard at a particular site is not yet possible because information on the frequency and occurrence of strong winds is not available. Nor is there enough information about the response of different species, crown classes, tree heights, or stand densities to high winds. There is a danger that any classification scheme will be misleading at times because of the nature of storm winds; however, intrinsic features of sites and management practices make certain stands either more or less prone to endemic wind damage.

A windthrow hazard classification has been developed based on the premise that certain conditions control or affect the wind force acting on trees and other characteristics that affect the resistance to overturning of trees. It is the balance or lack of balance between these two factors, (wind force and resistance to overturning) that determines the windthrow hazard. Considering the interplay between these two factors may be useful when trying to develop management strategies to prevent or minimize windthrow. It is also important to understand that certain characteristics may lead toward a low windthrow hazard in one situation but to a high hazard in another situation. For instance, some dense stands may be relatively windfirm along clearcut edges, yet these same stands can be very vulnerable to windthrow when thinned.

The *wind force* acting on the soil-root system to cause overturning is influenced by:

+ topographic characteristics - *exposure to and control of wind direction, velocity, and turbulence*

+ stand level characteristics - *density, canopy roughness*

+ tree characteristics - *height, diameter, crown form.*

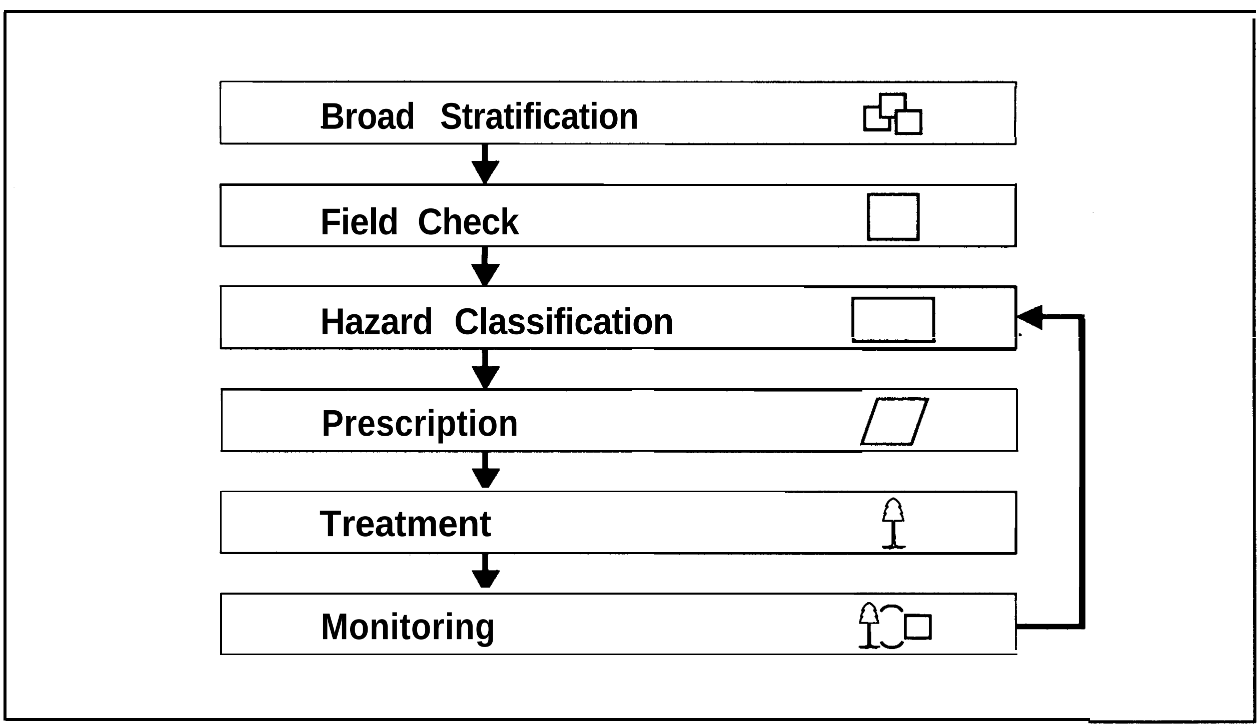

FIGURE 9. Windthrow evaluation flowchart.

Resistance to overturning is influenced by:

+ tree characteristics - *rooting, bole and butt form, presence of root and butt rots*
+ stand characteristics - *inter-tree damping*
+ soil characteristics - *depth, structure*, *texture, root restricting layers, and drainage regime.*

High risk stands (high wind force and low *resistance to overturning*) are located where poor root anchorage occurs, where high wind speeds and turbulence are more likely to occur, and where the stand structure and composition and tree form make it more liable to wind damage if openings are made.

Low risk stands (*low wind force and high resistance to overturning)* are located where good root anchorage occurs as a result of soil conditions, where topographic sheltering reduces the windspeed and turbulence, and where the stand and individual tree characteristics make trees less susceptible to windthrow after openings are made.

Moderate risk stands either have factors that contribute to poor anchorage but a low wind force, moderate resistance to overturning and a moderate wind force, or good anchorage but a high wind force. The latter case may be more stable than the former.

In addition to the above, many on-site indicators can be used to refine the assessment of the windthrow hazard. Certain areas have a reputation for being particularly windy. In windy areas the forest canopy is often deformed or asymmetrical, or branches are severely abraded. Adjacent cutblock boundaries can be assessed for the incidence and orientation of windthrow. Evidence of extensive windthrow or stembreak in the natural stand before cutting suggests that windthrow is likely to occur after cutting. Evidence of pit and mound micro-topography indicates that windthrow has occurred in the past and is therefore likely to occur again. Systematic documentation of the orientation of windthrow in the natural stand can indicate the expected direction of damaging winds.

Mapping of the spatial patterns of natural or management-induced windthrow may give an indication of which topographic locations in a local landscape are most vulnerable. Road cuts in the area can be used to better determine the spatial variability of factors that might affect root anchorage. Soil pits should be used to determine rooting depth, soil depth, soil moisture regime, and other factors mentioned above that affect the resistance to overturning.

Rooting depths are best determined by excavating soil pits l-2 m away from typical trees in the stand. Rooting depth is determined by measuring the depth from the top of the forest floor to the deepest live root, irrespective of size. If windthrown trees are present, an estimate of rooting depth may be taken from the root mass of the tree. Use of the rooting depth near the perimeter of the root mass rather than the center will likely produce a better correlation with rooting depths determined from soil pits (in some cases, rooting is deeper near the center of the root mass).

Though the site windthrow hazard is largely determined by inherent site features such as topographic exposure and rooting characteristics, the risk of windthrow can also change over time as stand structure and composition change and as management activities such as road development or adjacent cutblock locations affect wind flow and soil conditions. These dynamics should be considered in longer term management plans.

TABLE 1. Windthrow hazard evaluation

WIND FORCE FACTORS:		
HIGH HAZARD	MODERATE HAZARD	LOWER HAZARD
topographically exposed locations: crests, saddles, upper slopes, etc.		topographically protected locations
boundaries on the windward edge of a stand	boundaries parallel to the storm wind direction	boundaries on the lee edge of a stand
tall trees	trees of intermediate height	short trees
large dense crowns	moderately dense crowns	small open crowns
RESISTANCE TO OVERTURNING:		
HIGH HAZARD	MODERATE HAZARD	LOWER HAZARD
trees with low taper and no butt flare	trees with moderate taper and moderate butt flare	trees with high taper and large butt flare
shallow rooting	moderately deep rooting	deep rooting
(<0.4 m)	(0.4 - 0.8 m)	(> 0.8 m)
root rot areas		no evidence of root rot
shallow soils	moderately deep soils	deep soils
(<0.4)	(0.4 - 0.8 m)	(> 0.8 m)
poorly drained soils	imperfectly to moderately well-drained soils	well-drained soils
OTHER INDICATORS:		
HIGH HAZARD	MODERATE HAZARD	LOWER HAZARD
moderate to extensive natural windthrow present	minor natural windthrow present	no natural windthrow
extensive windthrow present on similar adjacent cutting boundaries	minor to moderate windthrow present on similar adjacent cutting boundaries	no windthrow on similar adjacent cutting boundaries
pit and mound micro-topography		no evidence of pit and mound microtopography

6 WINDTHROW MANAGEMENT STRATEGIES

Each windthrow hazard class has implications that might affect the feasibility and timing of management practices. On high-hazard sites, wind damage is likely to occur at some time during the rotation and should be considered carefully during the formulation of broad-scale plans and site-specific prescriptions. On moderate hazard sites, wind damage could affect the outcome of operational treatments and should be considered. On low-hazard sites, wind damage is unlikely to occur over a rotation and management for windthrow can be considered as a relatively low priority.

The objective of windthrow management strategies is to reduce the wind force acting on the crowns and to increase the anchorage strength of the soil-root systems of residual or boundary trees. This can be achieved by selecting treatment or boundary locations and orientations that favour low wind speeds and/or good anchorage and by selecting for or controlling how certain stand and tree characteristics are modified or develop over time. Using a combination of these strategies should further reduce the risk of windthrow.

6.1 Clearcutting and Protection Forests

Careful location and design of boundaries can minimize wind damage.

- Downwind boundaries (windward stand edges) should be located on sites that are at least risk. Windward stand edges should be located on deep, well-drained soils where trees are more likely to be deeply rooted. In mountainous terrain, fluvial debris flow fans often provide some of the most windfirm cross-valley boundary locations because their deep, coarse soils and well-drained character allow deep rooting. Leeward stand edges are usually quite windfirm, even when located on relatively high-hazard sites, because of the protection from the direct force of the wind that the upwind stand provides. If possible, cutblocks should be oriented with any long-axis in the direction of the storm winds.
- Utilize natural landscape boundaries to create windfirm edges (e.g. rock bluffs, bogs, non-merchantable timber, landslides or snow avalanche tracks).
- Avoid locating clearcut boundaries in areas that have evidence of previous extensive or chronic windthrow.
- If a windward stand boundary proves to be windfirm, adjust logging plans so that it is not logged in the short-term. Most endemic windthrow occurs in the first three years after cutting. Try to replicate the conditions on these boundaries to create additional windfirm boundaries.
- Stand edges should be left relatively uniform and smooth. They should not have sharp corners or indentations that are exposed to the wind.
- Avoid damaging the structural roots of trees along opening boundaries during falling and ground skidding operations and during backspar trail and road construction.
- Stand edges may need to be feathered to reduce windthrow incidence on high and moderate hazard sites. The goal of feathering is to selectively remove vulnerable trees along opening boundaries, leaving the more windfirm stems to protect the downwind stand. More than 15-20% of the total number of trees should not be removed. Excessive thinning will increase canopy roughness and result in greater energy transfer into the canopy, thus increasing the risk of windthrow. Similarly, as tree-to-tree contact tends to damp the sway period created by wind, excessive thinning will reduce this damping effect. (See Section 6.2).
- If possible, include poorly drained areas within an opening. Alternatively leave a buffer of well-drained soils between the poorly drained soils and the opening edge. Treat areas of shallow soils and other high-hazard sites in a similar fashion.
- If windthrow occurs along an opening boundary, do not simply salvage the windthrow and

establish a new boundary with the same topographic, soil and stand conditions. Re-establishing the conditions that resulted in windthrow in the first place will likely lead to further windthrow. Consider leaving the windthrown area as a protective buffer for the timber behind, especially if the windthrow appears to have stabilized. A boundary that is 3-4 years old and shows no evidence of fresh windthrow can usually be considered stable. Take advantage of the natural feathering which has occurred by removing only downed or damaged material. Alternatively, look for changes in topographic, soil or stand conditions that may result in a more windfirm situation, then establish a new boundary at that location.

- Establish a windfirm boundary and from that point, log progressively into the wind. This approach may be used at more that one location in an area so that the cut is well dispersed.
- Extensive areas of high windthrow hazard may require the progressive development of cutblocks to minimize exposure and to facilitate salvage of windthrown timber.
- If possible, openings, roads and trails should be located in such a way that when windthrow occurs, it can be salvaged with as little damage as possible to regeneration.
- Narrow leave blocks between openings tend to be vulnerable to windthrow. Widths on the order of 500 m or more are suggested.
- Deciduous types tend to be more windfirm than conifers provided that they are not over mature. They are often in a leafless condition during the windier seasons.
- Clearcutting or not cutting may be the most appropriate treatments for high hazard stands which contain current endemic windthrow. Whenever possible, avoid putting boundaries in these areas. It may be possible to use silvicultural systems other than clearcutting in second growth stands on high-hazard sites if these stands are thinned at an early age to develop their windfirmness.

6.2 Edge Stabilization Treatments

- Edge feathering can be used to reduce the drag force on boundary trees. Trees within the edge buffer should be removed in the following order of preference:
    1. Unsound trees, especially if they have a large crown. These include diseased, deformed, forked, scarred, mistletoe infested, and root rot infested trees.
    2. Trees with asymmetric or stilt roots.
    3. Trees growing on unstable substrates, e.g., rocky knolls, large boulders, nurse logs, poorly drained depressions.
    4. Tall non-veteran trees, especially with the above features or with disproportionately large crowns.
- Residual trees should be left in the following order of preference:
    1. Sound, well-rooted veterans (e.g. snag-top cedars) or deciduous trees.
    2. Sound trees (strong roots and good taper) with relatively small, open crowns.
    3. Sound snags, when safety is not compromised.
- Stem removal should not exceed 15-20% of the trees in a strip 20-30 m in from the edge of the stand. Excessive thinning will increase windthrow susceptibility. Edge thinning is not recommended in single-storied, high density stands.
- Topping and/or pruning (limbing) of vulnerable trees along opening boundaries may be necessary to protect and maintain critical areas such as streamside buffers, ungulate ranges, forage areas, and other critical wildlife habitat.
- Reducing the crown by 20-30% appears to be adequate to reduce the risk of windthrow for most trees.

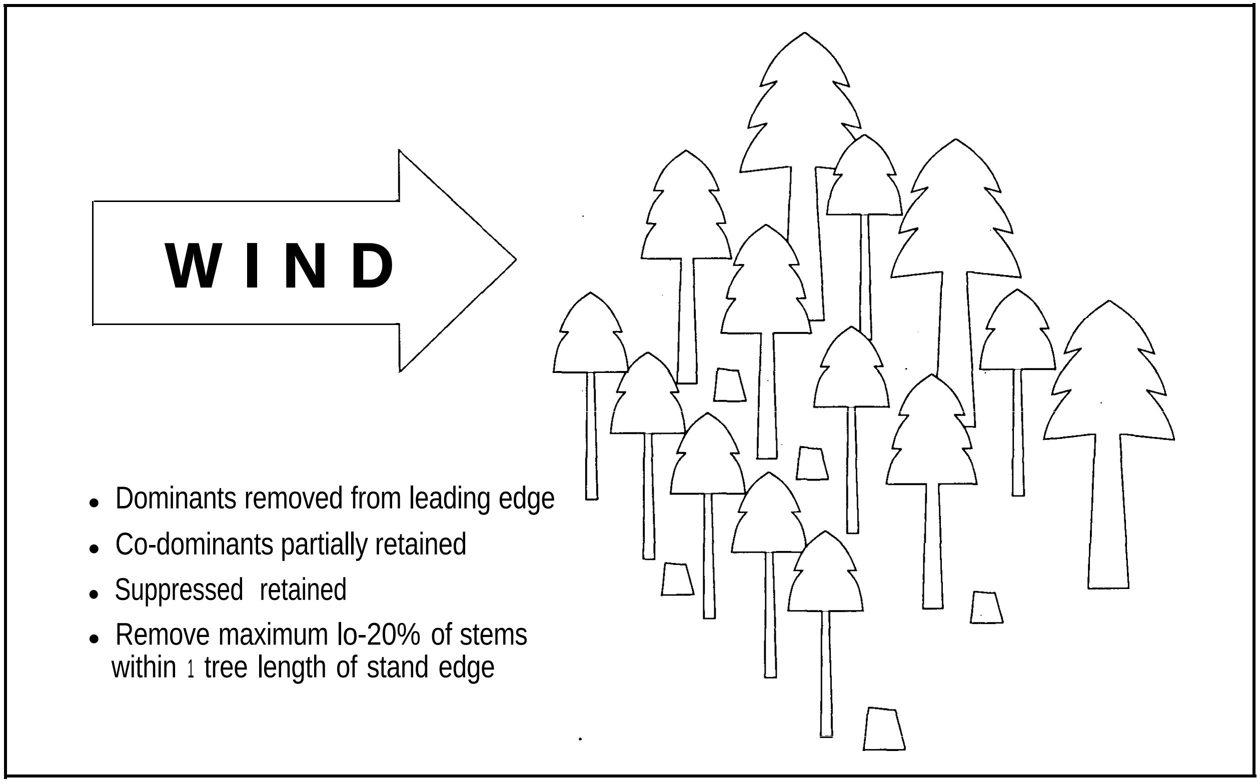

FIGURE IO. Edge feathering techniques in a multi-storied stand to stabilize the boundary of an opening.

+ A combination of edge-feathering and topping or pruning may be quite effective in high hazard areas.

6.3 Partial Cutting and Commercial Thinning

Partial cutting and commercial thinning treatments that open the canopy increase the drag force on individual trees and consequently increase their risk of overturning. They should be used cautiously on high and moderate windthrow hazard sites. The amount of canopy removal should also reflect the windfirmness of the original stand. Windfirm trees should be preferentially retained.

- ◆ When using group selection or strip cuts ensure that all high-hazard areas (e.g. poorly drained areas, areas of shallow soils, root rot pockets) are either completely logged or adequately buffered. These systems should be used with caution in high hazard zones.
- ◆ When leaving small groves or patches of timber, ensure that they are located on deep, well-drained soils or other sites where the windthrow hazard is low.
- ◆ Thin from below in uniform shelterwood cuts and commercial thinnings. Where possible avoid creating gaps greater than about one half tree length in these kinds of cuts.
- ◆ Avoid locating selection cuts, shelterwood cuts, or commercial thinnings at clearcut edges, especially if poorly drained soils, shallow soils or other high hazard conditions are present. Leave an untreated buffer between the opening and the treatment unit.
- ◆ When using selection or shelterwood systems on high-hazard sites, no more than 15-20% of the basal area should be removed in the initial harvest. The most vulnerable stems should be removed first, especially those with disproportionately large crowns or poor rooting conditions. Where initial

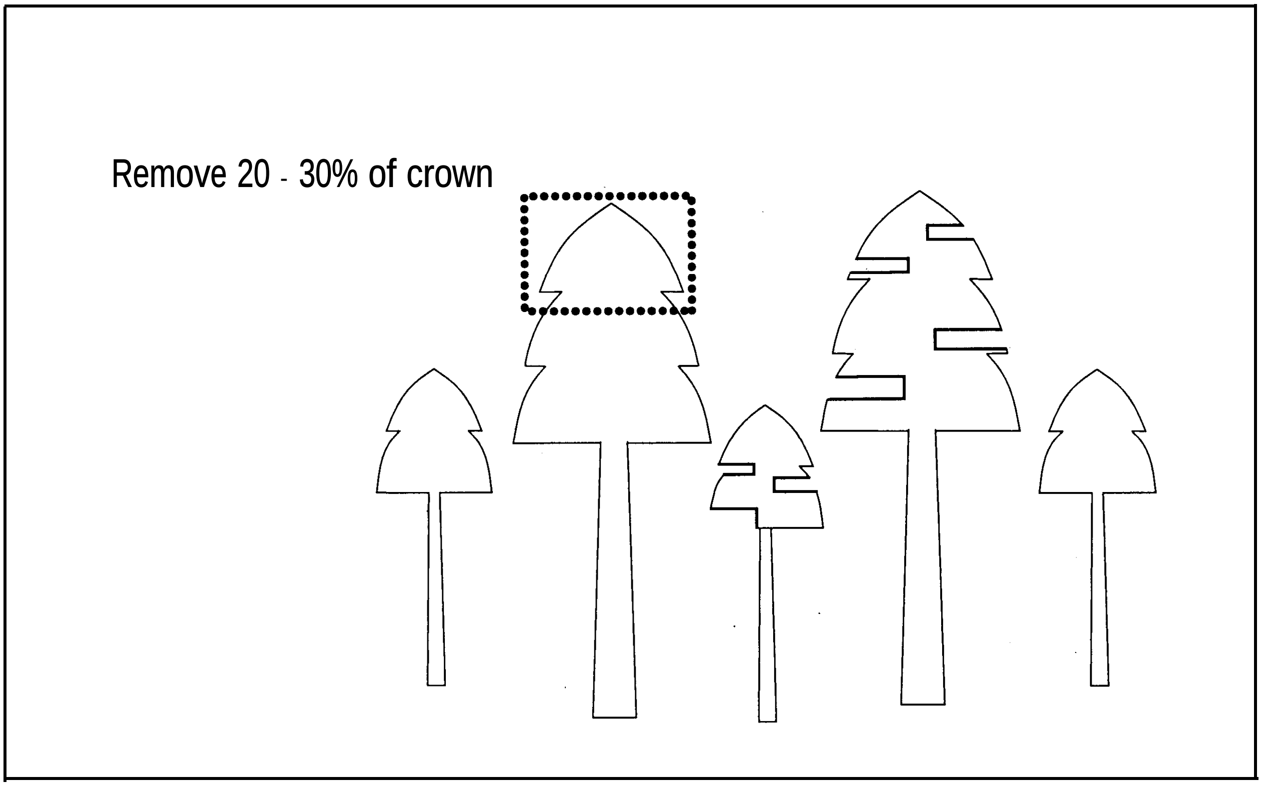

FIGURE 11. Topping and spiral pruning to reduce the wind force on boundary trees that have a high windthrow hazard.

stand densities are high, ensure that the opportunity for branch-to-branch contact between trees is maintained so that stem sway periods are damped.

- Commercial thinning should be avoided on high-hazard sites, particularly in very dense stands. If it is necessary, thin from below in a series of low intensity entries to reduce the probability of wind-related damage.
- Heavy commercial thinning of stands taller than 15-20 m is likely to result in considerable windthrow on high hazard sites. Late thinning should probably be done lightly, if at all on these sites.
- Trees with root systems damaged during yarding should be removed if their windfirmness is questionable.
- If windthrow occurs within a partial cutting treatment, reevaluate the windthrow hazard of the remaining trees within the stand before making the decision whether to 1) clearcut the stand, 2) salvage the windthrow and the remaining vulnerable stems, or 3) leave the windthrow. Removing or leaving windthrown timber will have other impacts that must be considered.

6.4 Regeneration and Stand Tending Treatments

Regeneration should be established on stable substrates on high-hazard sites. Trees growing on unstable substrates such as logs and old stumps should be preferentially removed during spacing. Some European research suggests that maintaining a deciduous component may improve the windfirmness of the surrounding conifers.

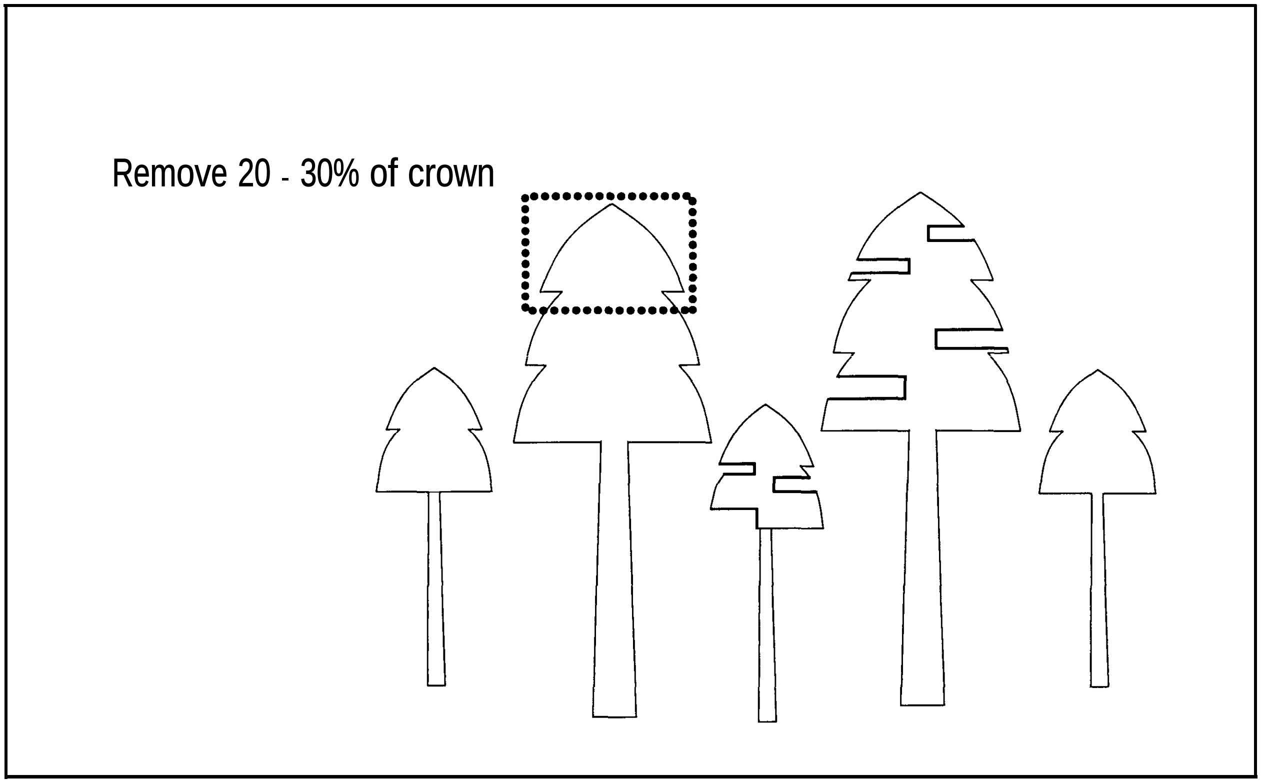

FIGURE 12. Edge feathering and topping to stabilize a high windthrow hazard boundary.

- Early spacing on moderate-to-high hazard sites will tend to promote windfirm stands in the long term. Alternatively, a dense stand can be maintained throughout the rotation.
- A series of light-intensity spacings or thinnings should be used on high-hazard sites rather than a single, heavy treatment. A period of several years should be left between each entry so that the residual stand has an opportunity to adapt to the new wind regime created by the spacing/thinning treatment.
- Some European research has indicated that fertilization immediately following late thinning treatments has resulted in increased windthrow. If this occurs the suggested solution is to delay fertilizing for several years following thinning to allow windfirmness to develop.
- Ditching and draining wet sites should be considered as a means of improving soil conditions and root anchorage on high hazard sites. Site preparation treatments which result in weak rooting and poor anchorage should be used with caution on high hazard sites.
- In high hazard areas where windthrow is severely damaging immature forests it may be necessary to develop harvesting schedules that are based upon the height of the dominant trees in the stand. This is becoming an accepted practice in some areas of the United Kingdom.

There are three basic strategies for regenerating windfirm stands on high to moderate windthrow hazard sites. These range from:

1. growing trees at a wide spacing to develop the natural windfirmness of each tree. This may result in knotty, low-density wood, but it may be a suitable strategy for sites where any type of forest cover is adequate (e.g. at very high elevations).
2. growing trees at a medium *spacing* either by planting at a medium density or using early thinning to promote windfirmness. The stand should not be thinned after the height exceeds

15-20 m. This will allow the canopy to close and increase the windfirmness of the stand during its more vulnerable older stage.

3. growing trees at a close spacing and harvesting at the onset of windthrow or at a specified height (e.g. 20 m) when the risk of windthrow approaches a critical threshold. These stands should not be thinned at any age because of the increased risk of windthrow.

6.5 Windthrow Monitoring

The objective of monitoring windthrow is to provide managers with feedback so that they may improve the hazard classification and refine treatment techniques. It is suggested that the broad scale maps used for the initial Hazard Evaluation be updated annually to show new windthrow. Major windthrow events should be documented by noting the date of the event, the peak wind speed and direction, and the rainfall recorded at the nearest climate station. A subsample of recent blocks from each of the strata identified on the broad scale map should be surveyed each year. A sampling method and sample field data form is provided at the back of this handbook.

7 SUMMARY

Windthrow is a natural process in forests and no forest or cutting unit will ever be completely immune from wind damage because of the nature of storm winds. Certain sites are inherently more prone to windthrow, either because of greater topographic exposure to damaging winds, poor root anchorage, or a more susceptible stand structure and composition. Losses resulting from windthrow can be significantly reduced by recognizing sites where it is likely to be a problem and using management practices to minimize its impact.

This guide provides only a brief synopsis of the literature on windthrow. The hazard classes are qualitative and only intended to serve as guidelines for stratifying high risk from low-risk sites. More quantitative approaches will be developed as more information becomes available on the characteristics of tree rooting strength under different soil conditions and through wind tunnel and field studies on the effects of landscape and stand characteristics on wind flow and force on tree canopies.

APPENDIX 1. Windthrow monitoring procedures and data forms

Windthrow monitoring procedures

Clearcut edges

Divide the perimeter of an opening into 15-30 segments of equal size. Randomly locate a 0.05 hectare (12.6 meter radius) circular lot in each segment. The outside edge of the plot should touch the original opening boundary. Record plot location, soil, topographic and standing tree characteristics. Record the attributes of any windthrow or windsnap whose point of germination is in the plot (see sample data sheet below).

Partial cuts

Two alternative monitoring systems are offered. For units with detailed timber cruise and soils maps and data, it may be necessary only to record the attributes and location of windthrow. Systematically locate strip plots 10 meters wide across the full width of the unit. Orient the strips so that they are non-parallel to slope and prevailing storm wind direction. Existing cruise strips may make good centerlines. Record strip length. Tally, map and record the attributes of any windthrow or windsnap whose point of germination is in the strip.

Alternatively, systematically locate 0.05 hectare circular plots ensuring good coverage of the unit. Record soil, topographic and standing tree characteristics. Record the attributes of any windthrow or windsnap whose point of germination is in the plot.

APPENDIX 1.

WINDTHROW MONITORING - EXAMPLE PLOT CARD

District: ____________ Licence: ________ C.P.: ______ Block: ________

Boundary Section: ____________ Plot Size: ________ Surveyor ________ Date: ________

Plot #:									
Boundary Shape:									
Boundary Aspect:									
Valley Orientation:									
Plot Aspect:									
Plot Slope:									
Plot Elevation:									
Slope Position:									
Eco. Association									
Soil Texture									
Rooting Depth:									
Depth impeding layer:									
Type impeding layer:									
#Standing Trees:									
Snag									
Veteran									
Dominant									
Co-dominant									
Intermediate									
Suppressed									
% Species Composition									
#Windthrown Trees									
Snag									
Veteran									
Dominant									
Co-dominant									
Intermediate									
Suppressed									
% Species Composition									
Direction of Fall									
#Windsnapped Trees									
Snag									
Veteran									
Dominant									
Co-dominant									
Intermediate									
Suppressed									
% Species Composition									
Direction of Fall									
Root Rot									
Bark Beetle									
Windthrow Hazard Class									

Comments:

APPENDIX 1. (Continued)

WINDTHROW HAZARD EVALUATION - EXAMPLE FIELD CHECKLIST

District: ______________________ Licence: ____________________ C.P.: _______________ Block: ______________

Boundary Section: ____ Surveyor: _____________ Date: ________________

Wind Force Indicators

Topographic Exposure:

- ☐ Crest
- ☐ Saddle
- ☐ Upper Slope
- ☐ Shoulder
- ☐ Bowl
- ☐ Valley bottom perpendicular to prevailing winds

Boundary Orientation:

- ☐ Windward
- ☐ Sub-parallel
- ☐ Lee

Stand Attributes:

- ☐ Uniform - high density
- ☐ Uniform - moderate density
- ☐ Uneven - high density
- ☐ Uniform - low density
- ☐ Uneven - low density
- ☐ Uneven - moderate density

- ☐ Taller than average
- ☐ Intermediate
- ☐ Shorter than average

Tree Attributes:

- ☐ Taller than average
- ☐ Average
- ☐ Shorter than average

- ☐ Large dense crowns
- ☐ Moderately dense crowns
- ☐ Small open crowns

Overturning Resistance Indicators

Tree Attributes:

- ☐ Low taper
- ☐ Moderate taper
- ☐ High taper

- ☐ No butt flare
- ☐ Moderate butt flare
- ☐ Large butt flare

- ☐ Root or stem rot
- ☐ No root or stem rot

Rooting Depth:

- ☐ Shallow (<O.4 m)
- ☐ Moderately Deep (0.4 - 0.8 m)
- ☐ Deep (>0.8m)

Soil Drainage:

- ☐ Poor
- ☐ Imperfect
- ☐ Moderate
- ☐ Good

Other Indicators

Windthrow in stand:

- ☐ Extensive
- ☐ Moderate
- ☐ Minor
- ☐ None

Windthrow along adjacent edges:

- ☐ Extensive
- ☐ Minor
- ☐ Moderate
- ☐ None

Pit and mound microtopoography:

- ☐ Extensive
- ☐ Minor
- ☐ Moderate
- ☐ None

Windthrow Hazard Class

- ☐ High
- ☐ Moderate
- ☐ Low

GLOSSARY

Damping: dissipation of energy in a tree through movement and contact of branches, foliage, stem, and roots.

Drag: friction caused by trees and surface features in the boundary layer.

Drag Coefficient: a coefficient that relates the amount of force intercepted by the canopy to the windspeed or the effectiveness with which momentum is transferred (downwards) across a turbulent boundary layer.

Shear Stress: a measure of the tendency for one part of a solid to slide past another. Units: N/m2.

Shear Strain: the angle through which material is distorted as a result of shear stress. Units: dimensionless.

Streamline: a line that indicates the direction of flow.

Stress: force applied per unit area. Units: Newtons per square meter (N/m2).

Strain: the change in length that occurs under a given stress. No units.

Static Force: a constant force applied to a body.

Sway Period: the amount of time required for a tree crown to move through a complete sway.

Sway Amplitude: the distance that the tip of the crown moves from the vertical to its outermost sway point.

Toppling: when a tree leans by pivoting around a point below-ground; different from windthrow where roots are torn from the ground.

Uprooting: when a tree falls with most of its larger roots intact, tearing up the soil in the process.

Stembreak: when a strong wind snaps the bole of a tree rather than uprooting it. Synonym: windbreak, windsnap.

Windfirmness: the ability to resist overturning. A function of both crown and rooting characteristics.

Windthrow: same as uprooting. Synonyms: windfall, windbreak, blowdown, windblow - imply that the cause of overturning is related to strong wind.

Windthrow Hazard: the susceptibility of a stand to endemic windthrow (by gale force winds that have a recurrence interval of 5-10 years).

Windthrow Risk: the probability of wind causing damage to a stand.

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