

AN ABSTRACT OF THE THESIS OF

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Title: Wind Direction and Effect of Tree Lean on Coarse Woody Debris Production.

Abstract approved:



John Sessions

The natural fall of trees in riparian areas is an important source of coarse woody debris for mountain streams, improving fish habitat and influencing stream morphology. Existing models consider the probability of coarse woody debris entering a stream channel based upon trees having a random direction of fall without consideration of tree lean or wind direction. This research presents (1) the results of a field study to document tree lean of conifers near streams in two stands in the Oregon's Coast Range and (2) a physical and probabilistic model to estimate the probability of a tree falling into the stream including the effects of tree lean and wind direction.

The measurement of 200 conifers along two creeks located in McDonald Forest found that tree lean varied from 1 to 34 percent uphill and 1 to 29 percent downhill on slopes of 1 to 88 percent. Approximately 75 percent of the trees leaned

downhill and 25 percent of the trees leaned uphill. A significant linear relationship was found between lean and slope although there was considerable scatter around the regression line. In general, the steeper the slope, the greater the tree lean downhill. When tree lean data was stratified by aspect, the linear relationship was higher for the NE and SW aspects, slightly weaker for the NW aspect and not related with slope for the SE aspect.

A physical model was developed for calculating the critical wind speed required to overturn a tree. This critical wind speed is a function of maximum resisting moment of the tree root structure, crown cross sectional area, initial tree lean and the angle formed between wind direction and lean direction on the horizontal plane.

A probabilistic model was developed for determining the probability that a tree could fall and reach the stream. This probability is a function of exceedance probability for a particular period of time, wind direction probability, tree location and tree height.

The models were applied to two old-growth coniferous stands. Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] trees were selected to illustrate how the models can be used. Results of this study indicate that tree lean is not a major factor with respect to influencing tree blowdown for the range of tree lean data collected from coniferous trees along streams in the study area. Tree lean could be a major factor if it was greater than that observed in this study.

Wind Direction and Effect of Tree Lean  
on Coarse Woody Debris Production

by

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# Wind Direction and Effect of Tree Lean on Coarse Woody Debris Production

## INTRODUCTION

Coarse woody debris is an important component of forest streams in the Pacific Northwest (Harmon et al. 1986). Coarse woody debris (CWD) is provided by the natural fall of trees in a riparian forest which improves fish habitat and influences stream morphology.

Several studies (Andrus and Froehlich 1987, Harmon et al. 1986, and Keller and Tally 1979) have concentrated their attention on different relationships between riparian forest and streams. Past studies (Harmon et al. 1986) consider stream temperatures and the effects of litter on the stream ecosystem. Others (Bisson et al. 1987) have considered root systems and coarse woody debris and their influence on stream morphology and fish habitat.

The influence of the riparian forest and its contribution through the volume of coarse woody debris to streams has not received much study. Not all trees adjacent to streams fall into streams. Some authors (Robison and Beschta 1990) have developed geometric and empirical equations for determining the probability that a tree can provide coarse woody debris to a stream given tree height and slope distance from the stream. The research related to this subject assumes that tree fall is random in direction. No research has studied other factors that may affect the probability of the tree falling into the

stream. An external factor such as wind speed has been mentioned in some papers as being important, because most CWD comes from live trees adjacent to a channel through windthrow (Van Sickle and Gregory 1990, Steinblums et al. 1984). Another factor which could affect the direction of tree fall is the initial lean of the tree. In steep areas next to streams, trees are often observed leaning downhill.

This study will provide information about the tree lean along streams in McDonald Forest and will develop a physical model relating tree lean and wind speed to the probability that a tree will fall and reach a stream. Applications of this model may help planners decide which trees will contribute to coarse woody debris.

## OBJECTIVES

The objectives of this study are to provide basic information on tree lean of conifers in riparian zones in McDonald Forest and to develop a model relating wind speed and tree lean in order to determine if tree lean can significantly affect tree fall into streams. In order to realize this study, this project will accomplish the following specific objectives:

1. Collect tree lean and tree location data along streams in the McDonald forest.
2. Develop a physical model which calculates the wind speed required to overturn a tree considering its natural lean.
3. Develop a probability model for a tree falling into a stream as a function of its location, natural tree lean and probability of a storm wind occurring from a specified direction.

## LITERATURE REVIEW

Riparian areas can be characterized as the area along a stream where the vegetation and microclimate are influenced by perennial and intermittent water, associated high water tables and soils which exhibit some wetness characteristics (Morman 1993). Riparian areas are zones that help, through the addition of coarse woody debris (CWD), to achieve several objectives: structure fish habitat, trap sediment and shape channels.

Coarse woody debris usually consists of pieces of trees that are large enough to influence stream hydraulics and morphology and fish habitat, and that meet a minimum length requirement (Robison and Beschta 1990). CWD may be delivered to the stream from branches or crowns that have fallen off standing trees, as well as from trees falling directly into the stream channel (Van Sickle and Gregory 1990). CWD inputs into the stream are therefore a function of the density, height and species composition of the stand near the stream (Van Sickle and Gregory 1990). Effective management of riparian forests requires accurate estimates of current and future CWD input rates resulting from various silvicultural strategies in riparian areas (Van Sickle and Gregory 1990).

The probability of a tree falling into a stream has been modeled by several researchers. Rainville (1986) produced probabilistic estimates of the number of trees per decade

falling into stream channels for three western coniferous habitat types. Geometric and empirical equations, based on tree size and distances from the stream, were used by Robison and Beschta (1990), to determine the conditional probability of a tree adding CWD to a stream.

A probabilistic model was developed by Van Sickle and Gregory (1990). They estimated the debris input based on the density (trees per unit area), tree size distribution and tree-fall probability of the riparian stand adjacent to the stream. Distribution of volume, length, and orientation of delivered debris pieces were also predicted.

The probability (Pd) of a piece of CWD entering a stream channel with trees having a random fall has been given by McDade et al. (1990) and Van Sickle and Gregory (1990) as:

$$Pd = \frac{\cos^{-1}(D/H)}{180^\circ}$$

where

D = source (perpendicular) distance (ft)  
from streambank to the tree.

H = tree height (ft).

A geometric equation developed by Robison and Beschta (1990b) which determines the probability of a tree of coarse woody debris exceeding a minimum diameter of 8 inches falling into channel is:

$$Pd = \frac{\cos^{-1}(D/He)}{180^{\circ}}$$

where

He = effective tree height (ft) to the minimum diameter

D = distance of tree away from stream ( $0 \leq D \leq He$ )

Both models assume a completely random direction of tree-fall. Random fall would be expected in flat or gently sloped riparian forests where trees do not lean strongly toward the channel and mortality agents such as windthrow do not have preferred direction (Van Sickle and Gregory 1990). On steep slopes, rooting asymmetry and downslope tree lean may result in towards-channel falling (Van Sickle and Gregory 1990). In fact, the probability of a tree falling downslope may be relatively high. The acquisition of information on the direction of tree fall in riparian zones would allow further refinement of the probabilities of tree fall (Robison and Beschta 1990).

In summary, previous studies have not directly considered either tree lean or the effect of wind as variables related with the natural fall of trees into the stream. However, they mentioned these variables as contributing factors for determining if coarse woody debris would reach a stream.



## Soil Type and Moisture

Many researchers (Day 1950, Fraser 1962, Busby 1965 and Alexander 1967) have recognized that soil type and moisture characteristics are important factors contributing to blowdown. Soil depth, texture, cohesion and drainage can directly affect the rooting depth and rooting strength of trees. According to literature, trees on deep soils are more windfirm than shallow soils. Shallow soils generally lead to shallow and relatively weak root systems and blowdown (Gratkowski 1956 and Alexander 1967).

In general, effective rooting depth is usually more important than soil depth (Moore 1977). Some characteristics such as cemented layers, clay layers, layers of gravel or other layers result in shallow effective rooting depth.

Texture is another important soil factor because of its effect on drainage and rooting depth. On coarse textured soils, rooting depths will be greater and trees more windfirm (Moore 1977). In fine textured soils, the roots will be shallower and trees more prone to blowdown.

Faulkner and Malcolm (1973) pulled forty Scots pine trees growing in five different soil types to investigate the variability of tree stability with soil type. The greatest values of stability were reported for trees growing in sandy soil with decreasing stability for trees in silt and clay soils.

Fraser (1962) studied soil and root factors in tree stability and determined the angle of maximum resistance for Douglas-fir and Sitka spruce growing on different soils through pull tests (Figure 1).

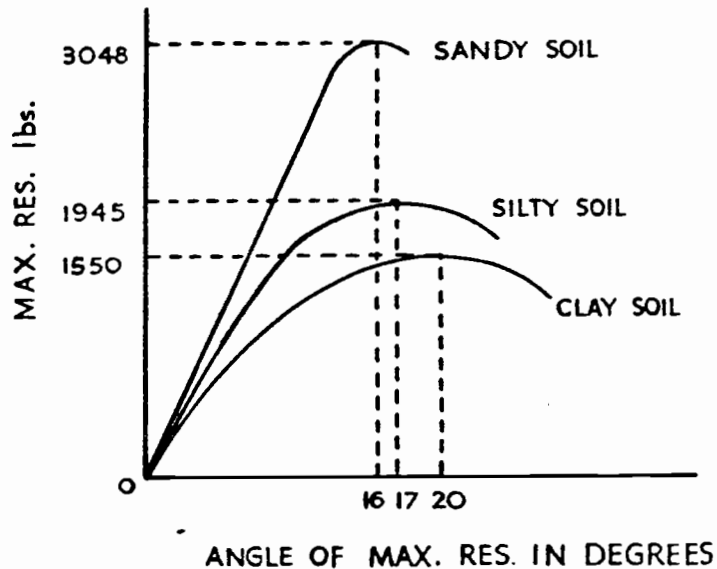


Figure 1. Comparison of pull-deflection curves for trees growing on different soils (From Fraser 1962).

The moisture content and drainage conditions of the soil affect the available rooting volume. Drainage reflects soil texture and is a useful indicator of blowdown. Poorly drained soils indicate a shallow root system which results from fine textured soil or the presence of an impermeable or cemented layer in the soil (Moore 1977).

Roots tend to avoid regions of high moisture stress. Conversely, fine root growth was restricted in soils of water contents less than ten per cent (Faulkner and Malcolm, 1973).

Well drained soils encourage deeper, larger root systems and are usually observed to be more windfirm. However, rapidly or excessively drained soils over unfractured bedrock have contributed to blowdown. Fraser (1962) reports that a controlled drainage can significantly increase rooting depth and the mechanical strength of the soil resulting in an increase in tree stability.

Because of rooting characteristics, and to a lesser degree the shape of their crown, an important issue affecting blowdown is tree species. Douglas-fir appears to be a relatively windfirm species. This tree generally grows on well drained sites and develops deeper root systems than other species. Even on shallow soil it develops extensive, heavy root systems and penetrates fractured bedrock.

#### Topographical Factors

The geographic location of the tree is important because of the inter-relationships between location and the factors of exposure to high winds and high rainfall. The local topography is a factor that contributes to blowdown because of its effect in accelerating winds and causing them to become turbulent.

Studies by Fraser and Gardiner (1967) on the effects of ground slope on tree stability revealed a lack of measurable difference in overturning moment between trees pulled uphill and downhill. However, the general form of the root system was

affected by ground slope. On slopes greater than 15 per cent there was a marked tendency for lateral roots to be concentrated on the downhill side and for well-buttressed vertical sinkers to grow on the uphill side.

### Windthrow

Very few studies about wind force have been found. Many authors have investigated the influence of different meteorological and site factors on blowdown, but none have expressed an idea about the critical wind speed needed for tree fall and how tree lean affects this process.

Wind conditions depend on the geographic location of the forest area, site elevation and the degree of geomorphic shelter provided by surrounding topography. Particular stand management practices such as initial tree spacing and thinning alter stand structure and may alter windthrow vulnerability (Miller, 1985)

Windthrow is a problem in several places in Oregon, and can be a major source of economic loss (Wade and Wittrup 1987). The storm damage from winds depends on meteorological conditions, storm wind speed, site and soil type, terrain, stand characteristics and physical condition of trees (Mayer 1989). A major meteorological factor is wind direction. Generally, winds that cause this blowdown are storm winds rather than prevailing winds (Moore 1977). For example, in

Oregon the prevailing winds come from the northwest quadrant. However, the majority of the destructive surface winds are from the southwest quadrant (Wade and Wittrup 1987). Under certain conditions very strong east winds may occur, but these are usually limited to small areas.

Wind speed causing blowdown is not well known, but it has been observed that most blowdown occurs during normal winter wind storms. Blowdown is often a result of trees which were long protected from the full force of wind, and after nearby harvesting, suddenly are exposed to the wind's full force, rather than of excessively strong freak winds (Moore 1977). The wind speed is slowed by friction over a forest. Friction is provided by the canopy and the wind speed in the canopy. The highest speeds are recorded some distance above the canopy, above an imaginary line called the frictional boundary, where the frictional effect of the canopy is lost (Fons 1940). When the forest is cut, the frictional boundary is lowered and the highest wind speeds are found much closer to the ground. Thus trees left in a leave strip are not only suddenly exposed to wind, but are also exposed to winds of higher velocities. In addition the wind will speed up through a clearcut because the frictional resistance of the ground is less than that of a forest canopy (Fons 1940).

Wind speeds up as it goes through a constriction or a narrowing in its path. It also becomes turbulent as it flows out of a constriction or as it flows over an obstacle

(Alexander 1967 and Gratkowski 1956). Windthrow is more severe on the "lee" or sheltered side of a ridge than on the "windward" or exposed side. This is accounted for by "lee flow" or the tendency of wind blowing across a ridge to follow down the slope with increased velocity (Gratkowski 1956).

Gloyne (1968) commented briefly on properties of the natural wind relevant to forestry by describing the features of large-scale wind systems, the possible effects of landscape features on wind near the ground surface and the effects of surface friction on low-level flow.

The problem of tree stability against wind has received great interest in recent years. Most knowledge dealing with tree stability, including model development, has emerged from tree pulling experiments. Fraser (1962) used wire cable and winch to simulate the wind force necessary to overturn a tree and derived relationships between tree size and the resisting moment of the root mass.

Faulkner and Malcolm (1973), working on heathland soil types, pulled trees over and compared their resistance with described profile and physical features. They found that root morphology was important for stability, as was stem weight and soil strength.

Oliver and Mayhead (1974), proposed an equation for calculating the wind speed within the canopy based on wind speed above the forest canopy. This equation is:

$$V_{H_i} = V_w * \exp[-a(1-H_i/H_{max})]$$

where  $V_{H_i}$  is the wind speed (m/sec) at height  $H_i$ ,  $V_w$  is the wind speed above the forest canopy,  $H_{max}$  is the height (m) of forest canopy, and "a" is a coefficient ( $a = 2.5$ ).

The factors that influence stem breakage of conifers in high winds were studied by Petty and Swain (1985). They calculated applied and resistive bending moments for various values of wind speed within the canopy and also the vertical distribution of crown weight.

All authors cited above have worked on different topics related to tree stability, but have not integrated their work to determine the critical wind speed which will create windthrow. None of the authors has investigated the tree lean as a windthrow variable.

## AREA DESCRIPTION

Study Site

The study site is north of Corvallis, Oregon, in the McDonald Research Forest, Oregon State University. Two areas, A and B, were chosen for this study (Figure 2) on the basis of having the same tree species and being near to streams. Area A Creek is located at SW1/4 of the SW1/4, Section 7, Tsp. 11 S., Rng. 5 W.W.M and Area B Creek located at NW1/4, SW1/4, Sec.3, Tsp.11 S. 5W. The slopes in Areas A and B varied from 1 to 88 percent, with an average of 48 percent in Area A and 42 percent in Area B. Elevations in Area A varied between 700 and 1000 feet, with an average elevation of 880 feet. For study Area B the elevation was between 560 and 660 feet, with an average elevation of 610 feet. Soils types on Area A were classified as Dixonville (DN) and Ritner (R) and for Area B as Price (Pr) and Jory (Jo).

Stand Description

The stands in both areas was characterized by old-growth forest composed of Douglas-fir [Pseudotsuga menziesii (Mirb.) Franco]. The mean stand age in Area A was 126 years and in Area B was 132 years. Average diameters for this species in Area A and B were 30 and 35 inches respectively. Average total tree heights were 142 feet in Area A and 160 feet for Area B.



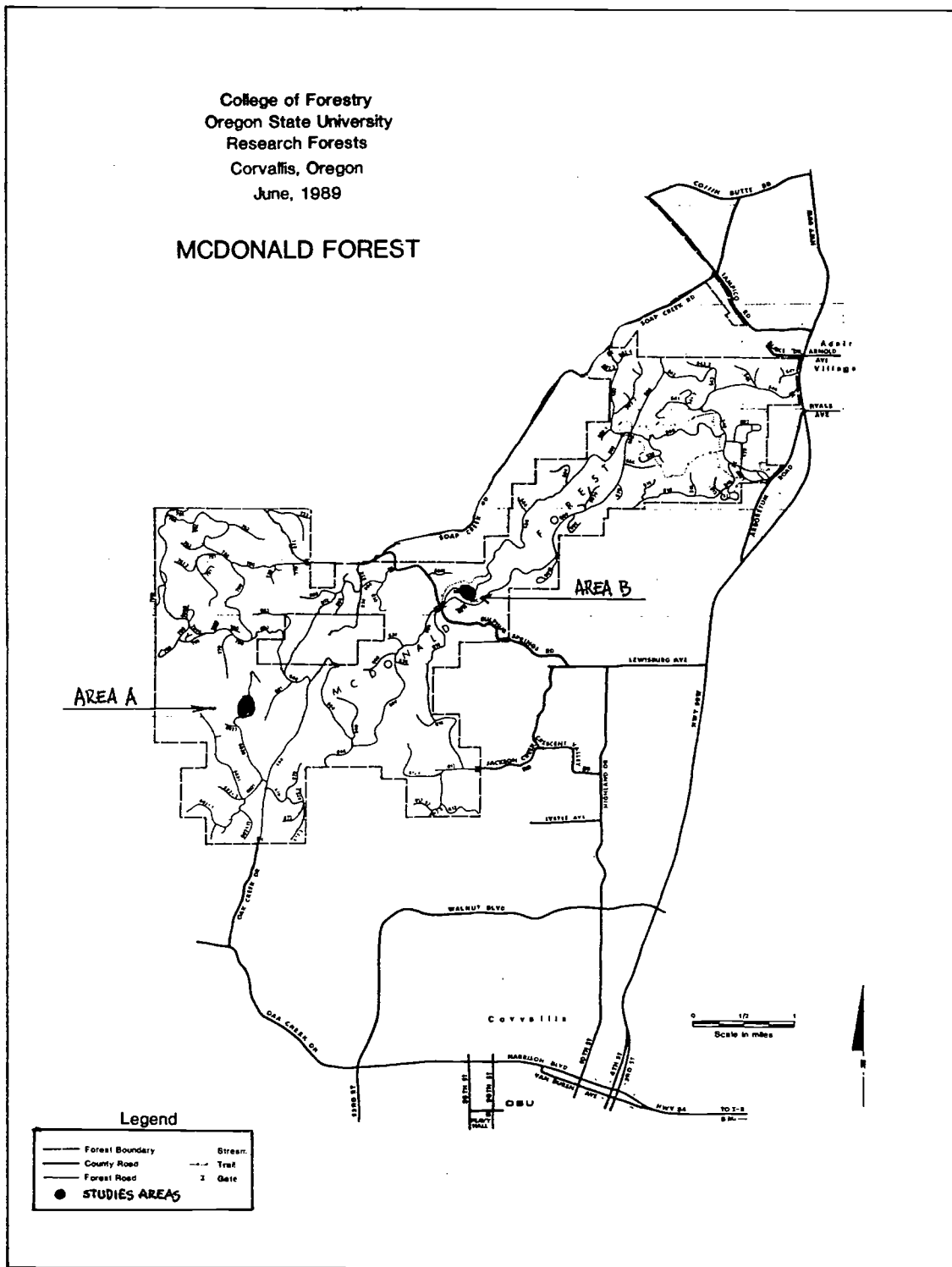


Figure 2. Study area location in west-central Oregon.

## METHODS

Two hundred trees were measured in this study area. A systematic sampling method was applied in Area A and B. The study area was defined by a strip width of 200 feet (slope distance) on each side of the stream.

The 200-foot slope distance was chosen based upon the maximum total tree height of dominant and codominant Douglas-fir trees growing on an average productivity site (McArdle et al. 1961). Since this study is concerned with wood delivery to streams, the tree would need to be close enough to the stream to fall into it.

The sample plots were defined as a rectangle of 50 feet x 200 feet located each 100 feet on both sides of the stream. The total area sampled was 5.51 acres. In every sample plot all mature trees were measured.

## Field Measurements

This study collected basic information about tree size, location and lean:

1. Variables related to the tree
  - a. Lean of the tree (%)
  - b. Total tree height (ft.)
  - c. Diameter breast height (in.)
  
2. Variables related to tree and stream
  - a. Downslope distance from standing tree to nearest channel boundary (ft).
  - b. Slope from standing tree to nearest channel boundary (%).
  - c. Distance of standing tree to stream in the direction of lean (ft).
  - d. Hillslope gradient in the direction of tree lean (%).
  - e. Azimuth angle for a horizontal line between tree and the nearest channel location (degree).
  - f. Azimuth angle for a horizontal line representing the direction of tree lean (degree).

A data form and data base collected from both areas are shown in appendix A, B and C respectively.

### Field Data and Techniques

In each sampling plot every tree was measured for tree lean using a lean measuring device (LMD). This instrument uses trigonometric relationships to directly measure tree lean (Appendix D).

The process used to measure tree lean was:

a) "Size up" the tree

Determine Lean Direction. This was determined by taking a general view of the tree from the base to the top to determine the natural lean of the tree.

b) At  $90^\circ$  from the lean direction a nail was attached to the center of the tree bole at 5 to 6 ft. above ground (Fig.3a). Then the lean measuring device was hung on the nail (Fig.3b) and the instrument centered so that a second nail hole was lined up with the lean of the tree. Both nails were placed in line with the axis of the tree (Fig.3c). After putting a nail into the second nail hole, the LMD was placed in position to measure the lean of the tree. The baseboard should (theoretically) be parallel to the lean direction (Fig.3d).

c) The carpenter's level on the LMD was then adjusted so that the bubble in the vertical level was perfectly centered, thus the carpenter's level was perfectly vertical (Fig.3e). The tree lean angle ( $\alpha$ ) could then be read directly from the LMD (Figure 3f). Any sweep or other form irregularities at more than 6 ft. above the ground were ignored.

The total tree height and diameter breast height (dbh), were measured by clinometer and diameter tape respectively. A distance tape was used to measure the perpendicular downslope distance from each standing tree to nearest channel boundary. The same method was applied to measure the distance from the tree into the stream considering tree lean direction. A compass was used for calculating the azimuth for both the angle to perpendicular distance to the stream and angle to lean distance to the stream.

The average field time required to collect all information was about 20 minutes per tree. Depending on terrain characteristics and the amount of understory or downed trees, the time might be more or less.

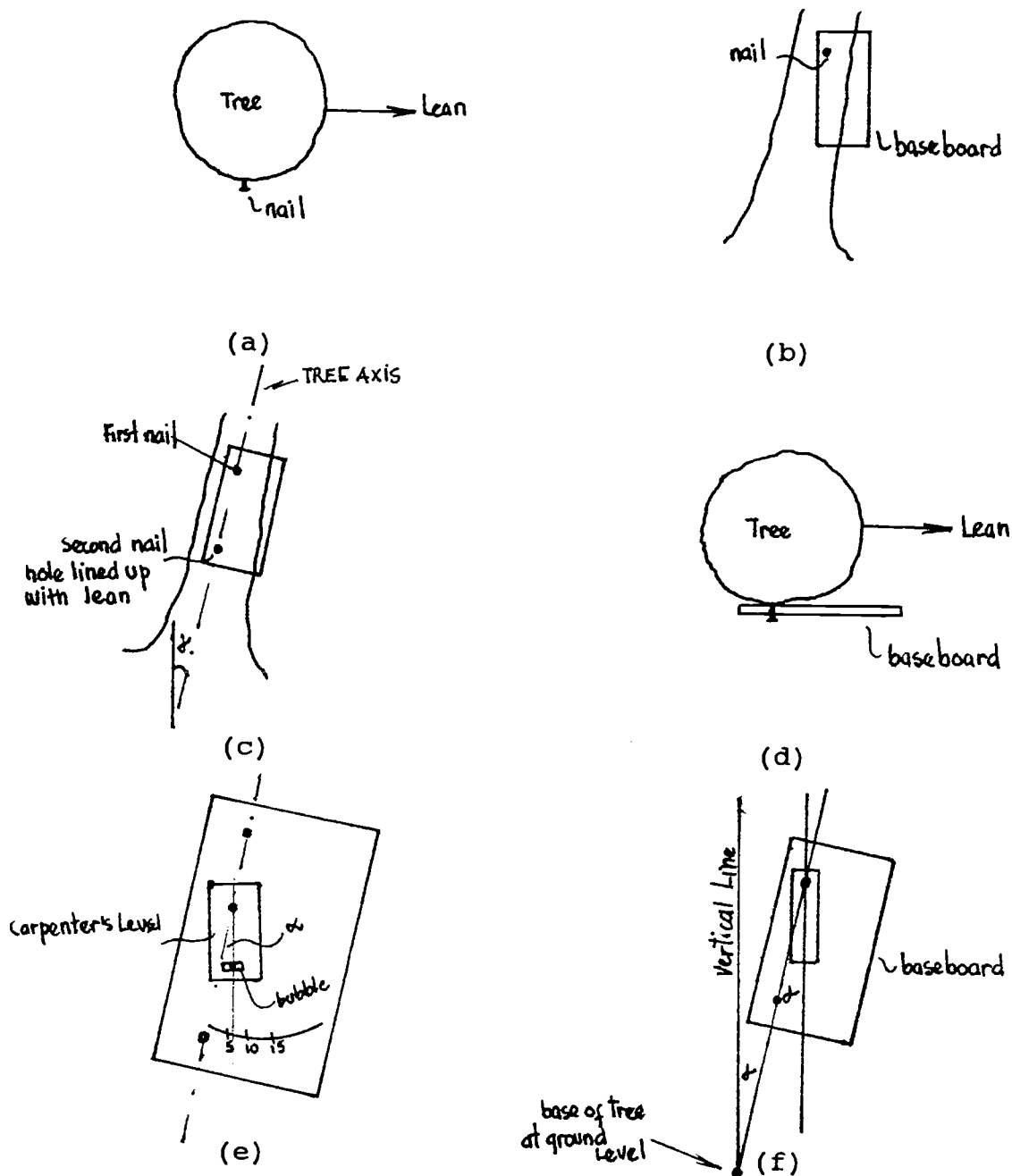


Figure 3. Tree lean measure sequence: (a) sizing up the tree, (b) attaching LMD to tree, (c) aligning base board along tree axis, view perpendicular to lean, (d) top view of base board, (e) adjusting carpenter's level to center bubble, and (f) reading tree lean angle.

## PHYSICAL MODEL DEVELOPMENT

The physical model represents an initial attempt to integrate wind, tree structure and root resisting moment. It is based upon the overturning moment of the tree and its relationship with the windload, tree weight and initial tree lean.

Assumptions

A number of assumptions have been made. Among the most important are:

1. The relationship between resistance to overturning and tree size will use mean relationships for root strength from published studies. This assumption does not consider that the trees which would be most likely to overturn would be those on the lower side of the regression line, that is, below the mean values of root-strength (Figure 4). These differences could be caused by soil factors, water level or root disease.

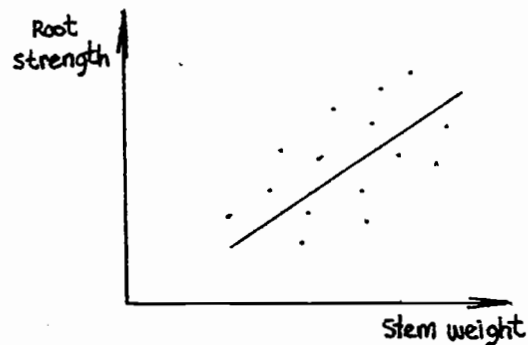


Figure 4. Relationship between root strength and stem weight. Data points represent individual tree measurements from pull tests.

2. Tree crowns were assumed symmetrical, that is, it is assumed that crowns on the uphill side of the tree do not differ from the downhill side of the tree so that the center of tree mass lies along the tree axis.

3. Windload acts at the center of wind force on the crown. Wind speed is assumed constant within the canopy and is assumed equal to the above canopy speed.

4. The air drag coefficient of the crown is not assumed to change as a function of wind speed. Air drag of the bole of the tree is not considered.

5. Reduced soil strength such as might occur after continued high rains prior to a windstorm are not considered.

6. Wind, in combination with the initial lean of the tree, is the only force creating an overturning moment. The additional moment created by tree weight as the tree leans under the force of the wind is not considered.

7. Additional tree loading such as ice or snow is not considered.

8. The failure mechanism is assumed to be overturning, not tree failure along the bole due to combined bending.

9. Trees are assumed to be acting independently (i.e., for modeling purposes). It is assumed that a tree is not affected by neighboring trees.

10. Root resistance was assumed to be the same in all directions.

11. Wind direction is assumed parallel to the slope.



12. Trees are assumed to be mature and do not grow during the period of analysis.

Suggestions for relaxing some assumptions are discussed in the Conclusions and Future Work section.

### Windload

The windload is assumed to act at the center of wind force on the crown (Mayer, 1989). The first moment,  $M_1$ , owing to the windload generated, can be calculated by:

$$M_1 = K_l * H_c \quad (1)$$

where  $H_c$  is the height to the center of wind force on the crown above the tree base (Fig. 5) and  $K_l$  is the windload.

The initial tree lean creates a second moment about the tree base,  $M_2$ , which can be calculated by:

$$\begin{aligned} M_2 &= W_t * L_d \quad \text{and} \\ L_d &= H_w * \sin \beta \end{aligned} \quad (2)$$

where  $L_d$  is the moment arm produced by tree lean between tree base and point a (Fig. 5) and  $W_t$  is the weight of the tree. Tree weight is represented in Figure 5 by the vertical force vector applied at G, the center of gravity of the tree. The position of G is defined by its distance  $H_w$  from the tree base, where  $H_w$  is the distance from the tree base to the center of gravity of the tree (ft). Adamovich (1979) used an  $H_w$  of 36% of the total tree height for Douglas-fir. This value for  $H_w$  was adopted in this study.

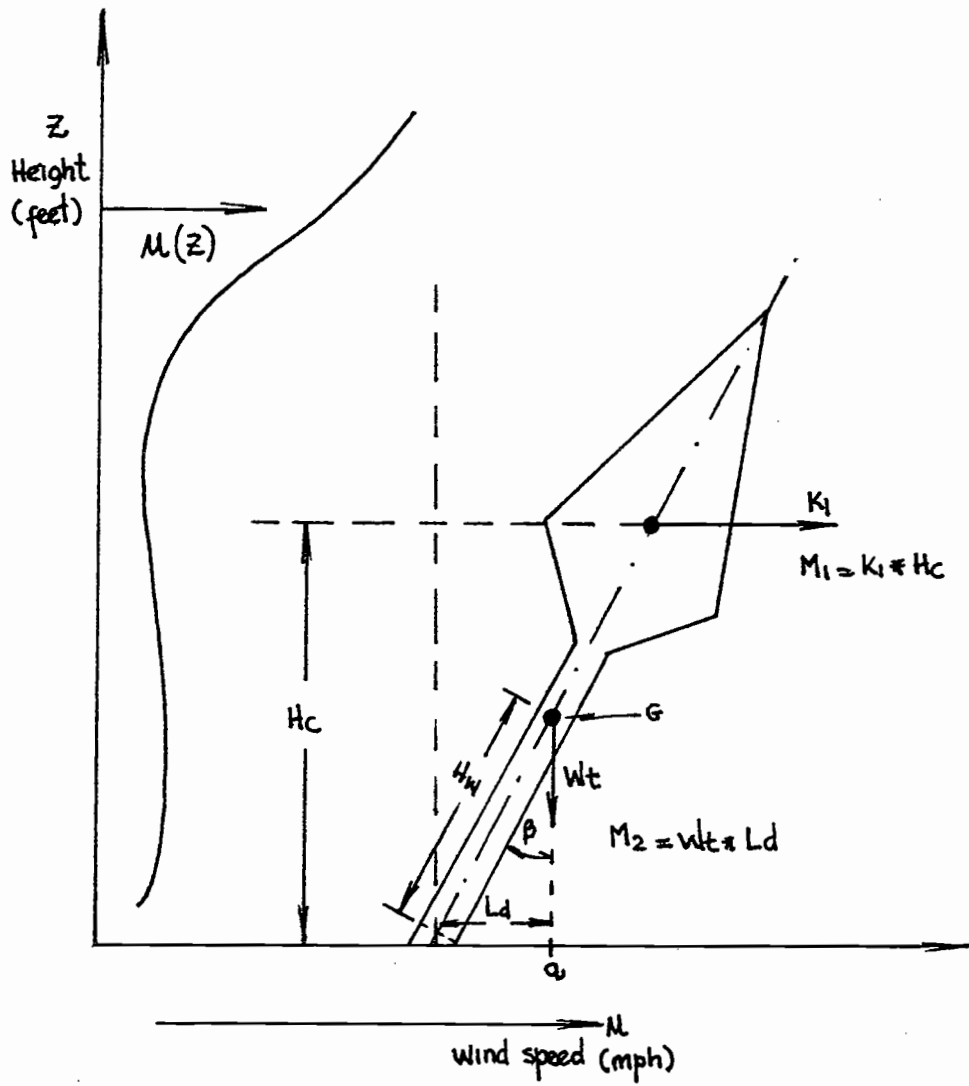


Figure 5. Windload on a tree and the resulting moments.

The resulting moment of the tree is the vector sum of the moment caused by the wind and the initial lean. In this study we assume a static force analysis using only initial windload and initial tree lean and do not attempt to model the additional moment caused by tree deflection in the wind.

Using these equations allows us to determine the wind speed to create a specified combined moment at the base of the tree taking into account the lean of the tree and the wind direction. The highest wind speed necessary to create a specified combined moment at the base of tree will occur when the wind is pushing opposite to the natural lean of the tree. The lowest wind speed necessary to create a specified combined moment will occur when the wind is pushing in the same direction of the natural tree lean. In this study we define the critical wind speed as that wind speed which in combination with the moment due to lean yields an overturning moment at the base of the tree equal to the assumed maximum resisting capability of the root mass.

If the wind could come from any direction relative to the tree lean, the critical wind speed would then depend upon wind direction relative to tree lean. We can express these relationships by developing an equation that considers the tree lean angle ( $\beta$ ) and the angle ( $\alpha$ ) formed by the lean direction vector and wind direction vector on the horizontal plane (Fig. 6).

Therefore, a general equation to express the maximum

moment for different wind direction and tree lean values is defined by:

$$MM = \sqrt{(K1*Hc*\sin\alpha)^2 + (K1*Hc*\cos\alpha*\cos\beta + Wt*Hw*\sin\beta)^2} \quad (3)$$

where

MM = maximum moment (lb-ft)

K1 = windload (lb)

Hc = height to center of wind force on the crown (ft)

Hw = distance to center of gravity of the tree (ft)

Wt = tree weight (lb)

$\alpha$  = angle that relates wind direction  
and lean direction

$\beta$  = angle related with tree lean value

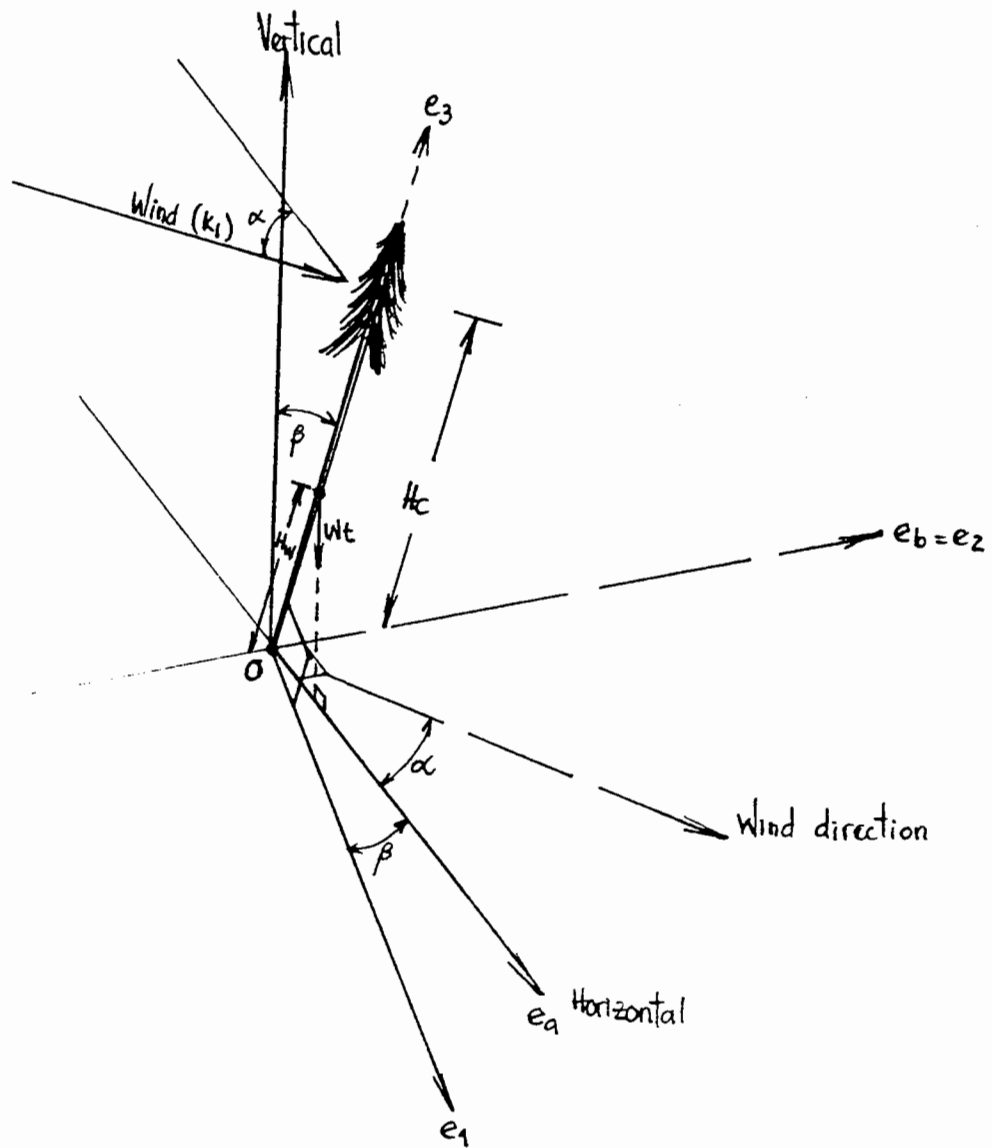


Figure 6. Relationship between tree lean, lean direction and wind direction.

### Windload Calculation

The windload acting on the tree can be estimated by either using a physical equation or an empirical formula. The starting point for the physical equation is the assumption, in the simplest case, of a free-standing tree that is an obstacle to air flow. The windload acting on the tree,  $K_l$  (lbs) (Mayer 1989), then is:

$$K_l = 1/2 * \rho_l / g * C_d * u^2 * A_c \quad (4)$$

where

$\rho_l$  = air density (lb/ft<sup>3</sup>)

$g$  = acceleration of gravity (ft/sec<sup>2</sup>)

$C_d$  = drag coefficient of crown (dimensionless)

$u$  = wind speed (ft/sec)

$A_c$  = cross sectional area of crown perpendicular to the air flow (ft<sup>2</sup>).

The air density is assumed to be 0.08 lb/ft<sup>3</sup>. The drag coefficient depends on the shape and orientation of the body. The maximum drag coefficient is experienced by surfaces at right angles to the windload. Deberdeev (1967) and Mayhead (1973) investigating the drag coefficient, found that  $C_d$  varied with wind speed because of the streamlining of leaves or needles. Guimier (1980) used a drag coefficient of 0.5 for conifers. This value was adopted in this study.

### Maximum Tree Resisting Moment

The resistance of the tree to falling is ultimately limited by the resistance to overturning of the root mass. Several investigators have investigated the root resisting capacity of trees. Some have been interested in determining the windfirmness of stands while others have been concerned with the ability of the roots to act as anchors for cable logging. Fraser (1962), interested in determining the windfirmness of trees, considered a number of factors including soil types and root system, but eventually settled upon using total stem weight as the only independent variable to predict the maximum moment resisting capacity of a tree.

Fraser's equation for the maximum overturning moment for Douglas-fir is:

$$MM = - 4270 + 73.58*Wt \quad (5)$$

where

MM = maximum moment (lb-ft)

Wt = stem weight (lb)

Other authors, interested in understanding the relationship between the holding capacity of stumps and stump size, have developed relationships between tree or stump diameter and the maximum horizontal force that can be applied at a given height above the ground. Pestal (1961) provides an equation relating the maximum stump holding capacity to the diameter of the tree

at breast height.

Pestal's equation for the maximum stump holding capacity is:

$$S_{\max} = \frac{D^2}{3}$$

where

$S_{\max}$  = maximum possible tension of skyline  
cable (tons)

$D$  = inside-bark diameter at breast height  
(decimeters).

It is not clear from the literature if this formula relates to the ultimate capacity of the stump or if it is the design load for the stump which incorporates some factor of safety. Stoupa (1984), studying the holding capacity of Douglas-fir in McDonald Forest, developed equations for the ultimate holding capacity of a stump as well as equations relating the holding capacity to ultimate moment capacity of the root mass. Stoupa's equations for the ultimate holding capacity of stump are:

$$\text{Ultimate Load on Stump} = 260.19(\text{DBH})^{1.99} \quad (\text{lbs})$$

$$\text{Depth to Point of Rotation} = 2.19(\text{DBH})^{1.28} \quad (\text{inches})$$

A comparison of the root resisting moment using Fraser, Pestal, and Stoupa equations are shown in Figure 7 using the diameter and estimated weight for a sample of trees from McDonald Forest. The details of the calculations are in



Appendix E. For Fraser, three curves are shown to illustrate sensitivity of the resisting moment to estimates of the tree density. Reported tree densities for Douglas-fir vary from 49 to 55 lbs/ft<sup>3</sup>. It can be seen that estimates made by Fraser are between Stoupa's and Pestal's estimates. Because Fraser's equation considers the entire tree, it can be more easily adapted in the physical model developed later in this paper. A tree density of 49 pounds per cubic foot is assumed for this study.

Pyles (1987), working with a beam-column of a skyline-logging tailspar, examined the taper of the spar tree, the flexibility of the base of the spar, and the eccentric restraining load at the top provided by guylines. In order to calculate the optimum guyline pretension which produced the greatest capacity in the spar tree, he expressed the resistance of the root mass as a function of the angle of rotation of the bole at ground level. Pyles' equation for the resistance of the root mass is:

$$M = K_b * \theta_b$$

and 
$$K_b = 4.13 * 10^{-4} * (IDBH)^{3.65}$$

where

$M$  = resistance of the root mass (KN-M)

$K_b$  = base stiffness (KN-M)/degree

$\theta_b$  = base rotation (degree)

IDBH = inside-bark diameter at breast height (cm)

Pyles' base stiffness equation might be useful in future modeling efforts and is discussed later.

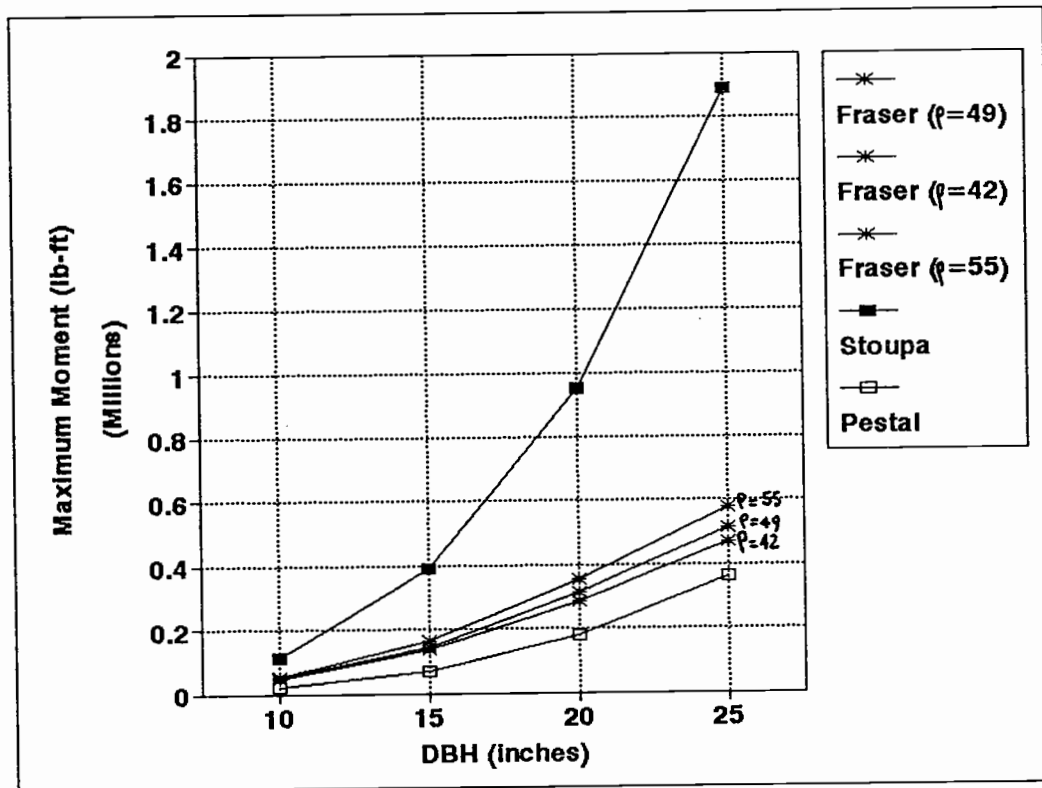


Figure 7. Comparison graphs of maximum resisting moment on DBH, using Fraser, Pestal and Stoupa equations ( $\rho$  = density of tree, lbs/ft<sup>3</sup>).

### Crown Cross Sectional Area

In order to evaluate the wind force on the tree, the crown cross sectional area of the tree must be estimated. Relationships between crown cross sectional area, total tree height, crown volume, and height from the ground to the live crown base have been developed by Biging and Wensel (1990) for three species in northern California.

$$A_c = \frac{k \cdot CV}{(H - HCB)} \left( \frac{H - h}{(H - HCB)} \right)^{k-1} \quad (6)$$

where

CV = total predicted geometric cubic  
volume of crown (ft<sup>3</sup>)

k = a species-specific parameter that  
determines the shape of the profile  
(for Douglas-fir, k = 1.805).

H = total tree height (ft)

h = height from HCB to H (ft).

HCB = height to live crown base (ft)

Equations for estimating total geometric crown volume, CV, were developed by Biging and Wensel (1990) for several conifers:

$$CV = a (DBH)^b * H^c * CR \quad (7)$$

where

$$CR = \frac{H - HCB}{H} \quad (8)$$

where

CR = crown ratio (dimensionless)

H = total tree height (ft.)

DBH = diameter breast height (in.)

HCB = height to live crown base (ft.)

a, b and c = coefficients that vary with tree species (Table 1).

The height to live crown base can be estimated using the taper equation of Walters and Hann (1986):

$$HCB = H / \{ 1.0 + \exp [ C_0 + C_1 * H + C_2 (H/DBH) + C_3 (H/DBH)^2 ] \} \quad (9)$$

$C_0, C_1, C_2$  and  $C_3$  are coefficients that vary with tree species (Table 2).

Table 1. Parameter values of coefficients for equation (7)  
(Biging and Wensel 1990).

Tree species	a	b	c
Douglas-fir	14.55286	0.97645	1.46273
White fir	9.57180	0.95171	1.56405
Red fir	9.57180	0.95171	1.56405
All species	7.91103	1.12450	1.72722

Table 2. Regression coefficients for predicting height to live  
crown base by species for equation (9) (Biging and  
Wensel 1990).

Tree species	C <sub>0</sub>	C <sub>1</sub>	C <sub>2</sub>	C <sub>3</sub>
Douglas-fir	3.674343	-0.012033	-0.529574	0.017875
White fir	3.727414	-0.014599	-0.340757	0.000000
Ponderosa pine	1.795295	-0.007186	-0.229465	0.000000

### Critical Wind Speed

The wind speed which creates an overturning moment equal to the maximum moment resisting capacity of the root mass can be developed by combining equations (3), (4) and (5). This wind speed,  $\mu$ , can be expressed as:

$$u = \sqrt{\frac{A \pm B}{C}} \quad (10)$$

where:

$$A = -Wt \cdot Hw \cdot \cos \alpha \cdot \cos \beta \cdot \sin \beta$$

$$B = [(Wt \cdot Hw \cdot \cos \alpha \cdot \cos \beta \cdot \sin \beta)^2 - (\sin^2 \alpha + \cos^2 \alpha \cdot \cos^2 \beta) (Wt^2 \cdot Hw^2 \cdot \sin^2 \beta - MM^2)]^{1/2}$$

$$C = \frac{1}{2} \cdot \rho l / g \cdot C_d \cdot A_c \cdot H_c \cdot (\sin^2 \alpha + \cos^2 \alpha \cdot \cos^2 \beta).$$

The derivation of equation (10) is in Appendix F. This equation (10) allows us to determine the critical wind speed ( $u$ ) as a function of tree lean angle ( $\beta$ ) and the angle ( $\alpha$ ) defined by lean direction and wind direction. Equation (10) must take only a positive value for B. The value A can be negative or positive, depending on angle  $\beta$ .

### Tree Fall Direction

The direction of tree fall is determined by considering the moments created by wind force and tree lean. Wind force,

wind direction, tree weight, and tree lean are variables necessary for calculating the direction the tree will fall.

The angle of tree fall will be along the vector of the sum of moments due to wind and tree lean in the x-y plane. To calculate the moments for the tree lean force and wind force the following equations are used:

$$\text{Moment due wind (Mw)} = \text{Wind force} * H_c * \cos\beta \quad (\text{lb-ft}) \quad (10a)$$

$$\text{Moment due tree lean (Ml)} = W_t * H_w * \sin\beta \quad (\text{lb-ft}) \quad (10b)$$

where

$H_c$  = height to the center of force on the crown (feet)

$\beta$  = tree lean angle (degree)

$W_t$  = tree weight (lbs)

$H_w$  = height to the center of gravity of tree (feet)

To calculate the x and y components of the moments due to wind and tree lean (Figure 6.1), the following equations were used.

$$M_x = M_w * \cos\theta_1 + M_l * \cos\theta_2 \quad (10c)$$

$$M_y = M_w * \sin\theta_1 + M_l * \sin\theta_2 \quad (10d)$$

where

$\theta_1$  = angle formed by  $M_w$  and the component x and y.

$\theta_2$  = angle formed by  $M_l$  and the component x and y.

And, finally the tree fall angle (azimuth) is given by:

$$\theta = \text{TAN}^{-1} (M_y/M_x) . \quad (10e)$$

Wind speeds higher than the critical wind speed will create a direction of fall more in line with the wind direction, but these are not considered in this analysis.

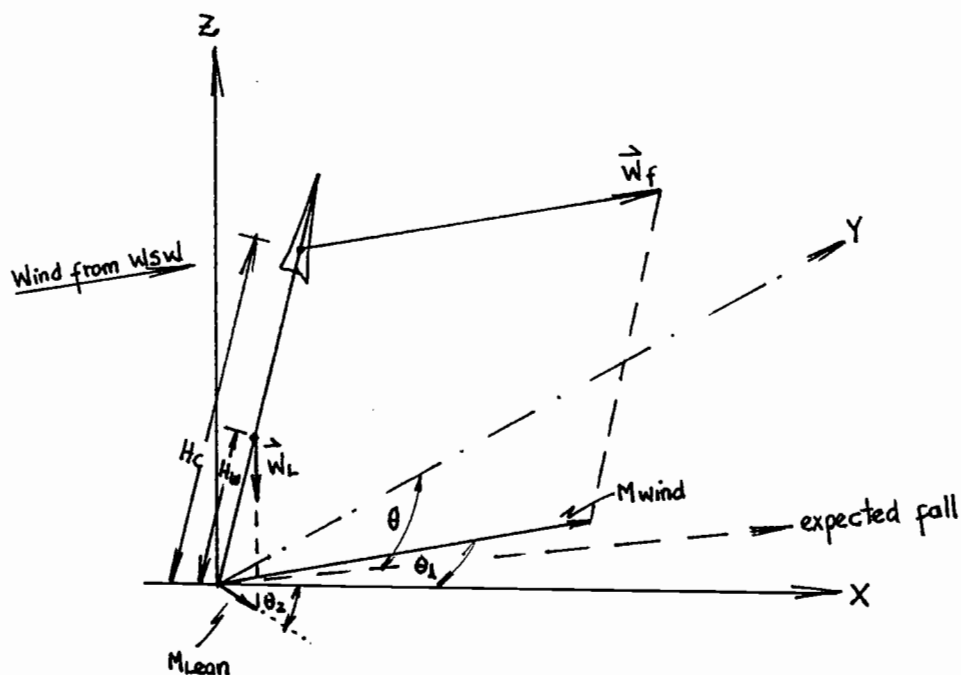


Figure 8. Tree fall direction considering a wind of critical speed coming from WSW.



## PROBABILISTIC MODEL DEVELOPMENT

A probabilistic model is used to determine the joint probability of a critical wind speed occurring from a particular direction and the falling tree reaching the stream.

Exceedance Probability  $P(e)$ 

The probability that a given wind speed will be exceeded within a one year period, will be represented by  $P(e)$ . In our case we need to know the Exceedance Probability  $P(e)$  for a critical wind speed from a given wind direction in McDonald Forest. Since wind data was not available for the study sites, wind data from local cities was used as a substitute.

Historical wind data was collected from stations located in Eugene, Salem and Corvallis (Appendix L) along with their associated return periods and extreme wind speeds (Figure 9). "Extreme" wind speeds describe abnormally strong winds that potentially could be damaging. These extreme wind events are relatively rare. The period of record for these data was 1943-1962 for Eugene, 1943-1977 for Salem, and 1962-1973 for Corvallis. Because of the short period of record for the Corvallis station, the average relationship of the Eugene and Salem stations was used because of their longer term record of data (Figure 10).

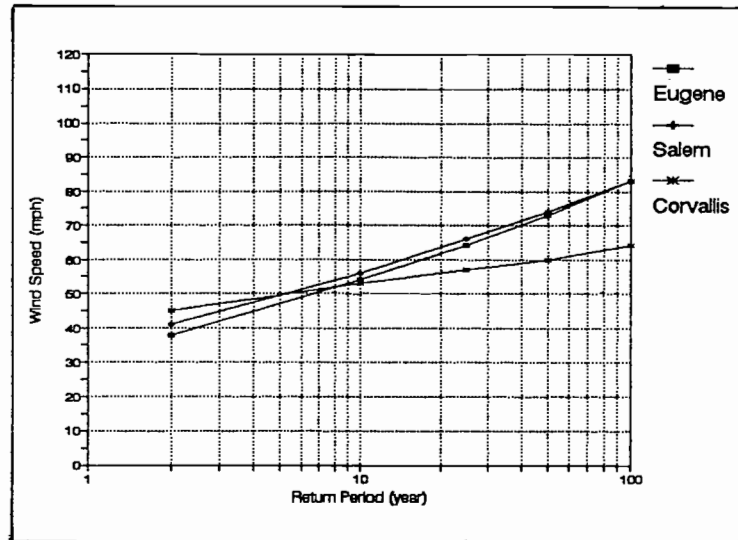


Figure 9. Return period (years) vs. extreme wind speed (mph) for Eugene, Salem and Corvallis.

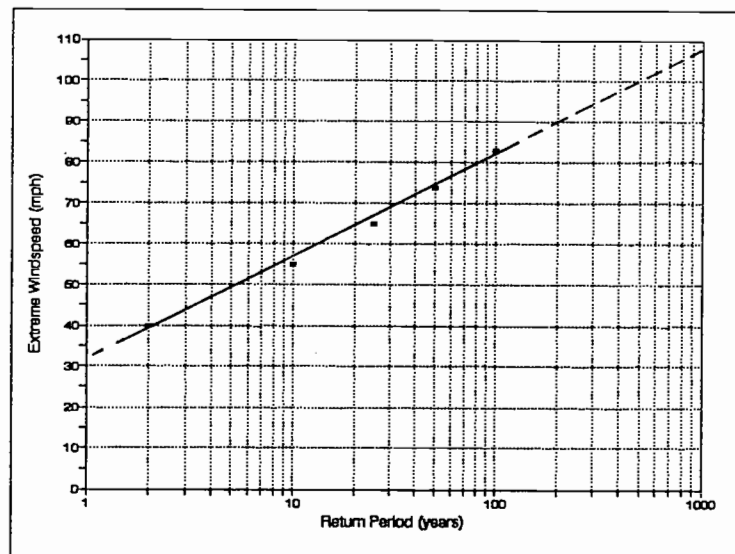


Figure 10. Return period (years) vs Extreme wind speed (mph) for averaged data between Eugene and Salem.

The exceedance probability  $P(e)$  for the critical wind speed over a longer period of time can be calculated from the following:

$$P(e) = 1 - \left( \frac{Tr-1}{Tr} \right)^n \quad (11)$$

where

$P(e)$  = exceedance probability

$Tr$  = return period (years)

$n$  = length of period (years)

#### Wind Direction Probability $P(d)$

The probability of wind coming from each direction was obtained from a record of wind frequency by wind direction for the Corvallis area (Appendix G). This table represents the wind speed values taken from data of several years during the month of February. The probability of storm winds by direction was derived from the percentage of time that winds greater than 16 mph have occurred from each direction.

Probability of Tree Fall P(f)

By combining the exceedance probability  $P(e)$  and probability of wind direction  $P(d)$ , we can obtain the probability of tree fall  $P(f)$  in a particular direction by calculating the joint probability of a critical wind speed occurring in a specified direction:

$$P(f) = \sum [P(e)_i * P(d)_i] \quad (12)$$

where

$P(e)_i$  = Exceedance probability for critical  
wind speed for wind direction  $i$ .

$P(d)_i$  = Probability of wind for  
direction  $i$ .

Probability of Tree Fall that Reaches Stream P(fs)

The probability that a tree falls and reaches the stream can be expressed by the following conditional probability:

$$P(fs) = \sum [P(e)_i * P(d)_i] * P(s) \quad (13)$$

or

$$P(fs) = P(f) * P(s) \quad (14)$$

Where,  $P(s)$  represents the conditional probability that a standing tree of height  $H$  reaches a stream at a distance  $D$ , given that it falls. If the tree can reach the stream, that is if  $D < H$ , then  $P(s) = 1$ . If the tree can not reach the stream, that is if  $D > H$ , then  $P(s) = 0$ . In this study we do not consider changes in tree height during the planning horizon.

## RESULTS

Field Data Results

Although the areas in the study are classified as old-growth areas, there are a considerable number of smaller (and younger) trees (Table 3). Tree diameters ranged from 10 inches to almost 77 inches dbh.

Table 3. Characteristics of Douglas-fir trees from Areas A and B.

Class Interval (DBH) (inch.)	Number of Trees	Average Height (ft.)	Average Volume (ft <sup>3</sup> )
10 - 15	37	92	33
15 - 20	12	117	76
20 - 25	33	135	144
25 - 30	22	141	209
30 - 35	19	158	319
35 - 40	22	172	439
40 - 45	5	187	614
45 - 50	21	204	814
50 - 55	10	213	1011
55 - 60	10	214	1214
60 - 65	5	208	1387
65 - 70	4	244	1998

An important part of this research was to measure the relationship between tree position, tree height and tree lean according to its distance from the stream.

Figure 11 shows the relationship between number of trees and slope distance from the stream.

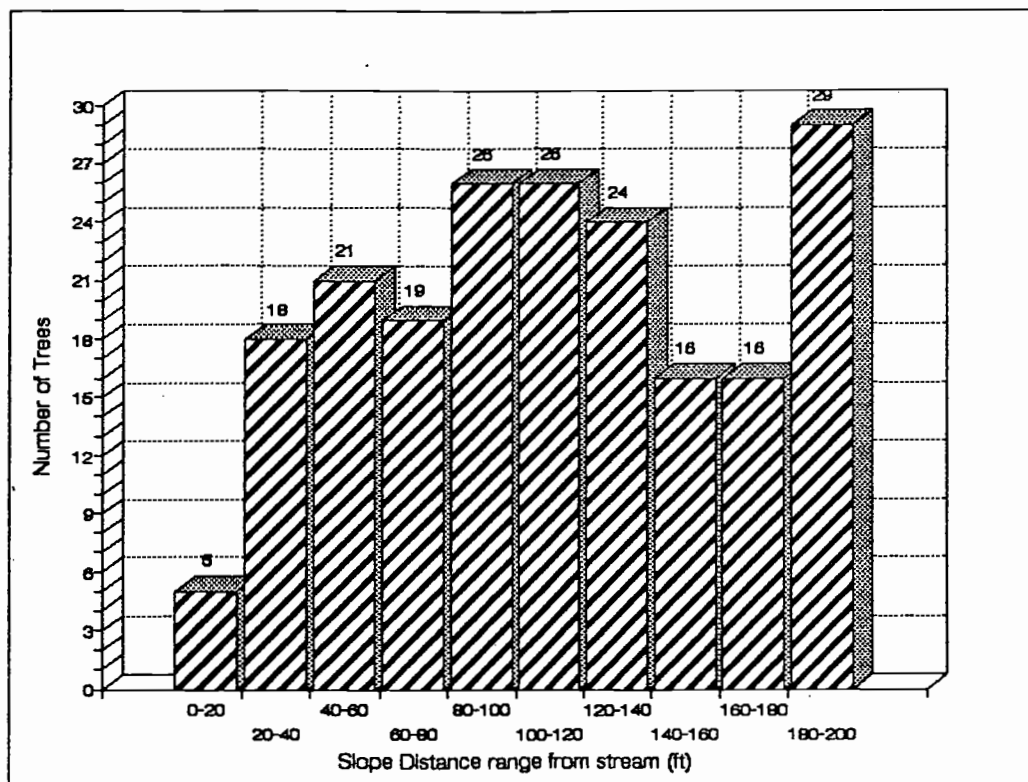


Figure 11. Relationship between number of trees and slope distance from stream (ft).

From Figure 9 it can be observed that a high percentage of trees, around 38% (76 trees), are distributed between 80 to 140 feet from the stream. The largest number (29) were between 180 to 200 feet from the stream. A low percentage of trees (2.5%) were close to the stream.

The average tree height for each distance range gives us an idea of tree height and tree location near the stream.

The relationship between average tree height and slope distance from the stream is shown in Figure 12. Average tree height was calculated considering the number of trees and their height by slope distance range. The tallest trees are within 80 feet of the stream (Figure 12). Between the ranges 80 to 160 there was a decrease of tree height followed by a small increase in the range between 160 to 200 feet from the stream.

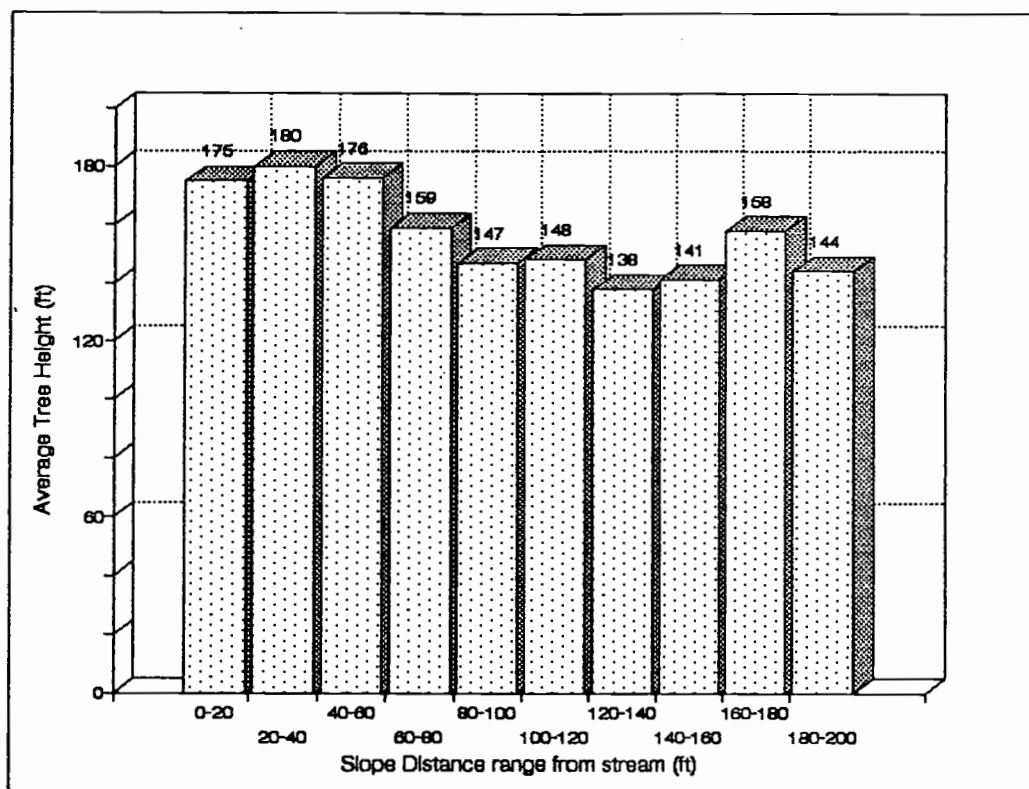


Figure 12. Relationship between average tree height (ft) on slope distance from stream (ft).



From the information collected from the field data, 44% of the trees within 200 feet slope distance of the stream had sufficient height to reach the stream and also leaned toward the stream (Figure 13). Without considering wind direction and speed, this means that 88 trees of the total 200 trees would have a high probability of reaching the stream, all other things being equal. About 17.5% of the trees were too short to reach the stream even though they leaned toward it. These trees would not reach the stream regardless of wind direction. Finally, 38.5% (77 trees) of the trees lean away from stream. Of these, 33 trees would be too short to reach the stream even if the wind blew them over against their lean and 44 were tall enough to reach the stream if the wind overcame the lean.

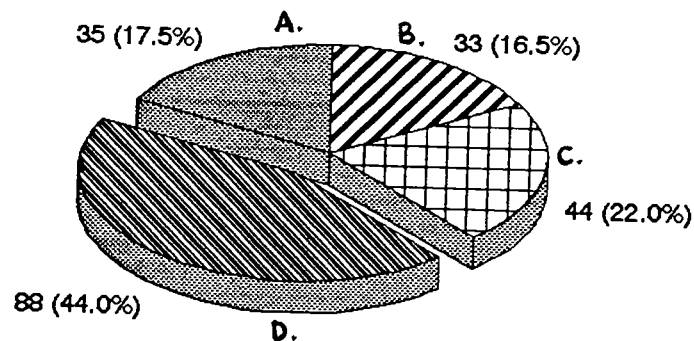


Figure 13. Percentage distribution of trees by lean, tree height and distance from stream. Where (a) trees are too short to reach stream, but they lean toward it; (b) trees are too short to reach stream, even if the wind blew them in that direction; (c) trees are tall enough to reach stream if the wind overcame the lean; and (d) trees are tall enough to reach and lean toward the stream.

Sampling plots on Area A and B had different aspects with respect to the streams (Table 4). The aspect for each sampling plot was determined by considering each individual tree and its aspect and then weighting the trees in the sample plot.

Table 4. Aspect for each sampling plot in Area A and Area B.

AREA A Sample N°	ASPECT	AREA B Sample N°	ASPECT
1	SE	1	NE
2	NW	2	NW
3	NW	3	NW
4	SE	4	NE
5	SE	5	SW
6	NW	6	NW
7	SW	7	NE
8	SE	8	SW
9	NW	9	NW
		10	NW
		11	SW
		12	SW
		13	NW
		14	NE
		15	NW

An important objective in this study was to collect tree lean data. If tree lean could affect direction of tree fall, then it is important to understand its magnitude and where it occurs. Some authors, for example, Conway (1973), have suggested that tree lean varies with ground slope. The data collected from the McDonald Forest was fitted to a linear model to determine if these variables were related. A scatterplot (Figure 14) and a plot of the residuals (Figure 15) are shown.

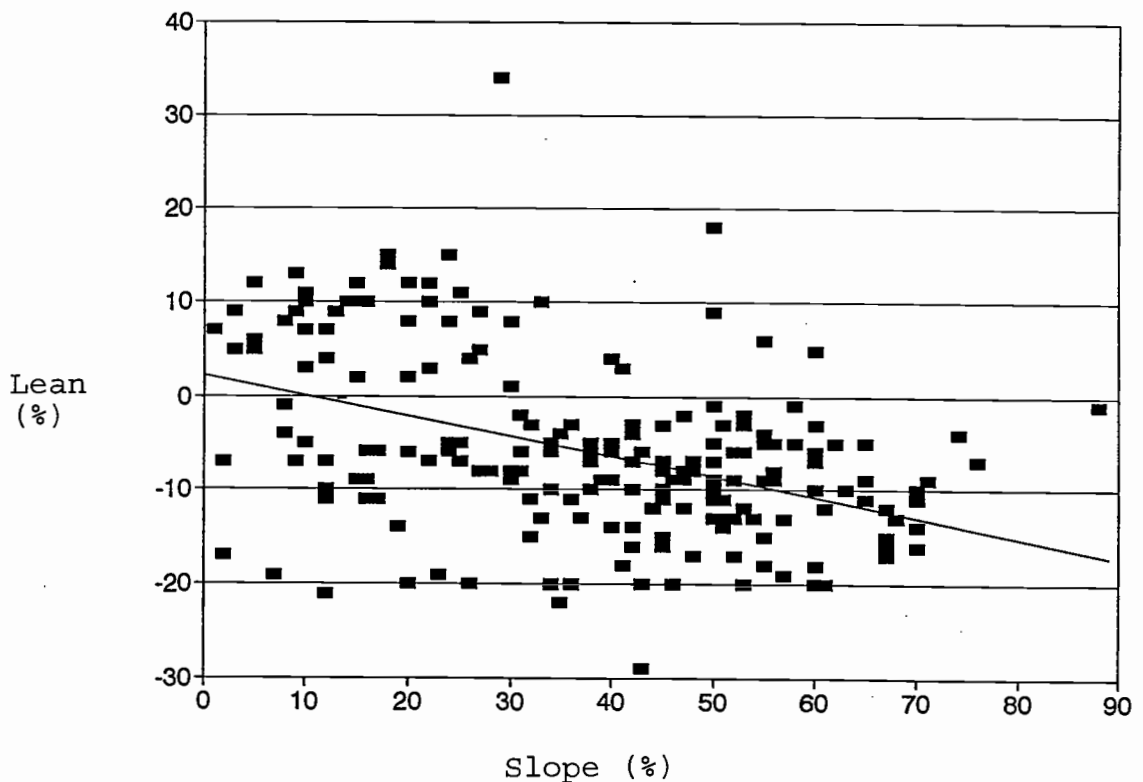


Figure 14. Scatterplot. Regression of tree lean (%) by ground slope (%). Positive values indicate lean uphill, negative values indicate tree lean downhill.

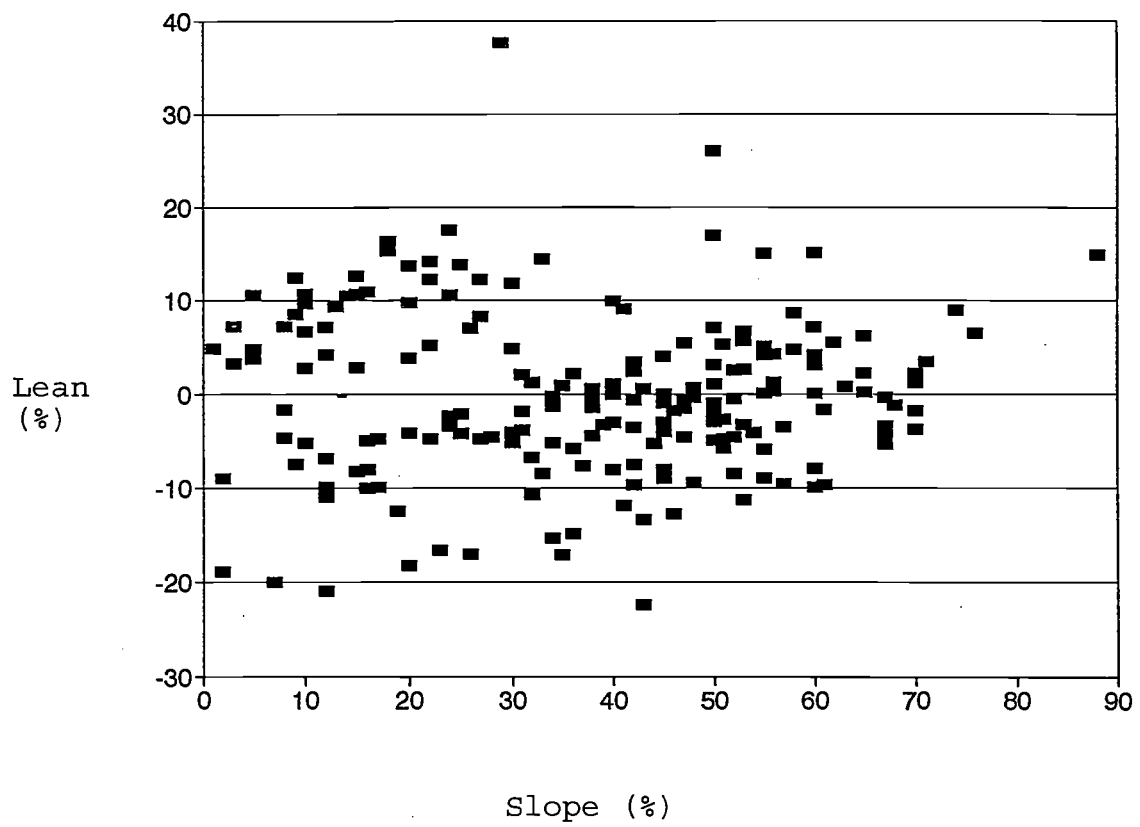


Figure 15. Residuals plot. Regression of lean (%) by slope (%).

A regression analysis through a linear model was applied to determine correlation between tree lean and slope.

Table 5. Field data analysis of variance. Regression of lean on slope not stratified by aspect. Significance values test null hypothesis at 95% confidence level.

Regression Analysis - Linear model: $Y = a+bx$ $R^2 = 0.17$				
Dependent variable: LEAN(%)		Independent variable: SLOPE(%)		
Parameter	Estimate	Standard Error	[T] Value	Significant
Intercept	2.3806	8.7678	0.27	No
Slope	-0.20838	0.03282	6.35	Yes

According to the results from Table 5 there is a significant relationship between lean and slope; the greater the slope the greater the lean downhill. However, there is considerable scatter around the regression line and the correlation coefficient (0.41) is low. It is reasonable to expect that the regression line would go through zero lean at zero ground slope. The value of the Y-intercept is low (2.38) and is not significantly different from zero when tested at the 95% level.

In order to determine if lean was being influenced by aspect, a regression analysis through a linear model was applied to determine correlation between tree lean (%) and slope (%) stratified by aspect (azimuth). Scatterplots and residual plots by each aspect are shown in Figure 15 and Figure 16.

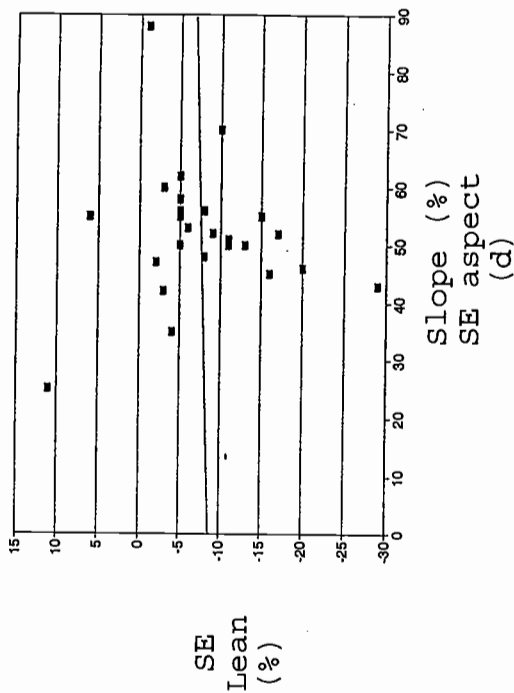
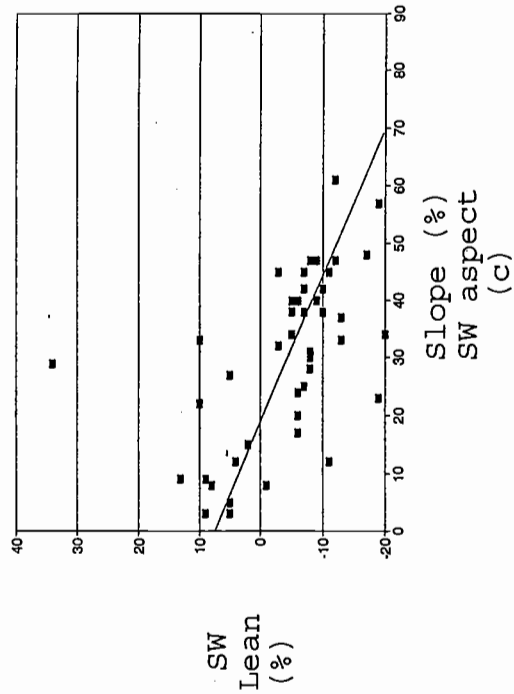
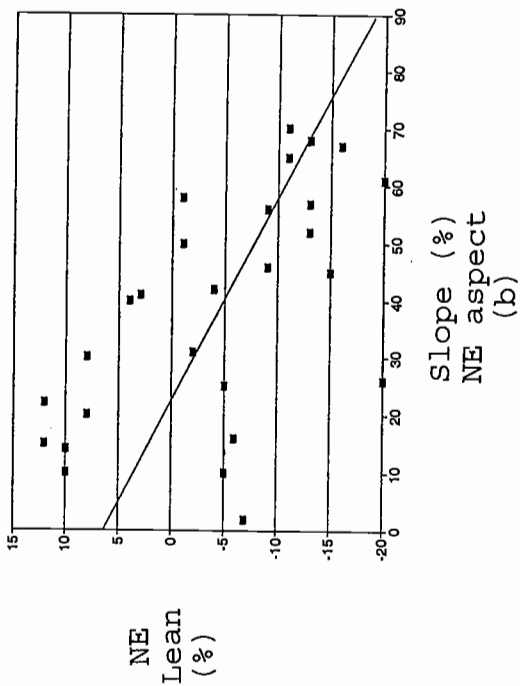
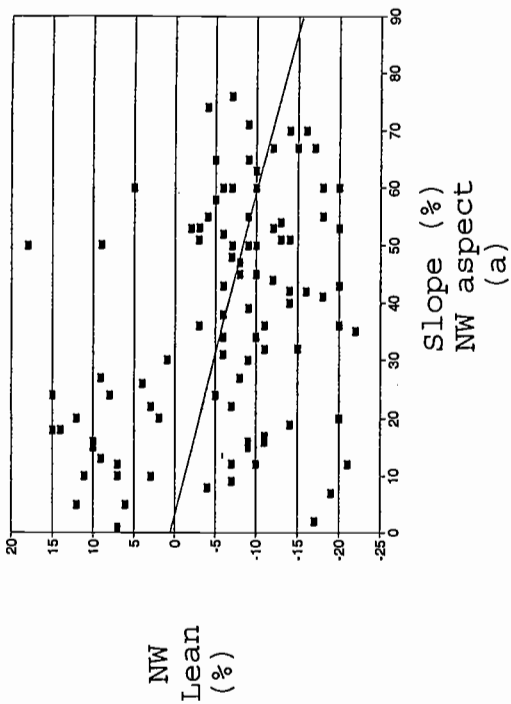


Figure 16. Scatterplots. Regression lean (%) on slope (%) stratified by aspect. Positive values indicate lean uphill, negative values indicate tree lean downhill.

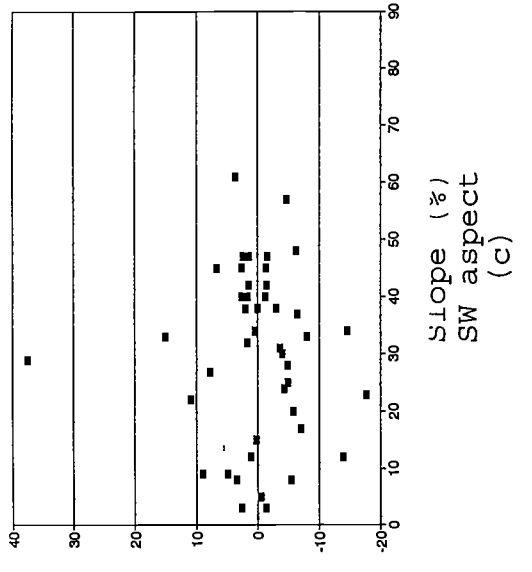
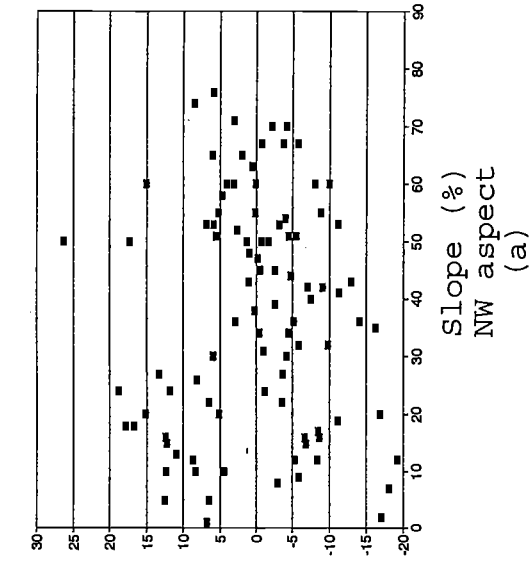
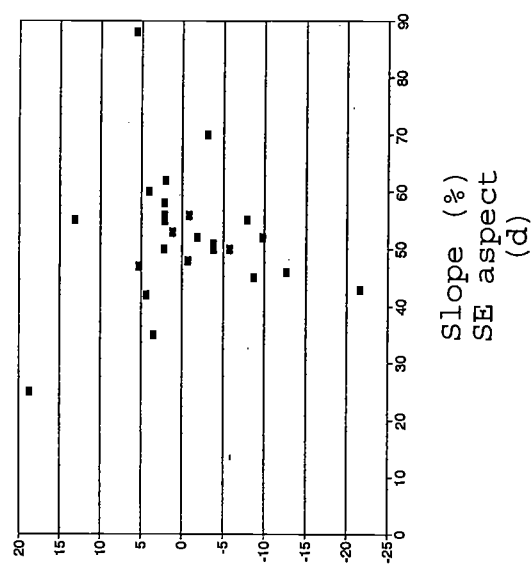
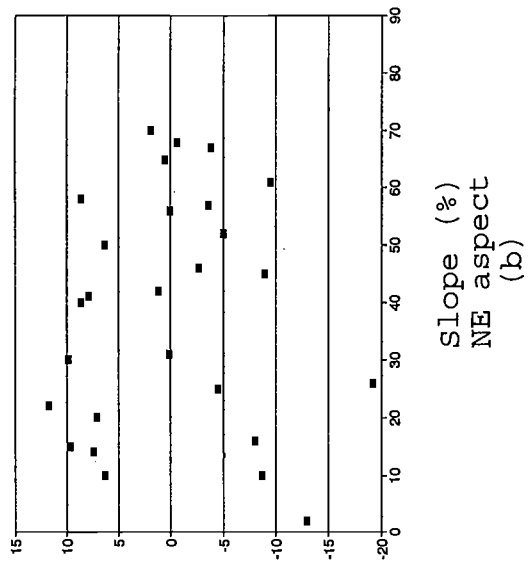


Figure 17. Residual plots. Regression lean (%) on slope (%) stratified by aspect.

Table 6. Regression of lean on slope when stratified by aspect (a) NW, (b) NE, (c) SE, (d) SW. Significance values test null hypothesis at 95% confidence level.

---

Regression Analysis - Linear model:  $Y = a+bx$

---

	NW	NE	SE	SW
Y-intercept	0.3804	6.4416	-8.0997	7.5120
SE of intercept	8.9745	8.1502	8.5725	8.4283
X-coefficient	-0.1741	-0.2771	0.0166	-0.3812
SE of coefficient	0.0460	0.07756	0.1510	0.0823
[T] of intercept	0.04	0.79	0.94	0.89
[T] of coefficient	3.78	3.57	0.11	4.63
Intercept significant	No	No	No	No
Coef. significant	Yes	Yes	No	Yes
R-squared	0.13	0.34	0.00	0.32

---

The stratification of data by aspect showed a significant relationship between lean and slope for all aspects except the SE aspect (Table 6). There was an improvement in R-squared values for the NE and SW aspects over the non-stratified analysis, although there was still considerable scatter around the regression lines.



### Model Application

In order to determine the probability of a given tree falling into a stream during a specified time period, it is necessary to carry out the following steps:

1. For each possible wind direction, calculate the critical wind speed required to exceed the maximum root resisting moment using Equation 10. We consider that there are 16 wind directions.

2. For each wind direction calculate the probability that a wind equal to or greater than critical wind speed will occur during the specified time period.

3. Then, identify which wind directions will cause the tree to fall into the stream,

4. Finally, add the probabilities associated with those wind directions which were identified in step 3. This sum represents an estimate of the probability that the tree will fall into the stream during the specified time period.

To illustrate the procedure with a numerical example, we consider the probability of Tree No. 2 from Area A falling into the stream during the next 100 years.

Step 1

We begin with calculating the critical wind speed for each direction considering the statistics for Tree No. 2 (Table 7). To facilitate the calculations, a computer program was developed to calculate the critical wind speed (Appendix K).

Table 7. Statistics for Tree No. 2, Area A.

DBH (in.)	Height (feet)	Volume (ft <sup>3</sup> )	Slope distance to stream (feet)	Angle to stream (az)	Tree lean (deg.)	Angle of lean (az)
28	141	205.9	51	86	6.3	152

Table 8. Critical wind speed and return period for critical wind speed for each wind direction for Tree No. 2. Return periods are based upon Figure 10.

Wind Direction	Critical wind speed (mph)	Return period (years)
N	99	450
NNE	100	460
NE	101	510
ENE	103	630
E	104	690
ESE	106	800
SE	107	890
SSE	107	890
S	106	800
SSW	105	750
SW	104	690
WSW	102	590
W	101	510
WNW	100	460
NW	99	450
NNW	99	450

The critical wind speeds and return periods for each direction are shown in Table 8. The return periods are based upon the relationship in Figure 8. The maximum wind speed required to overturn the tree is calculated when the wind is going opposite the natural tree lean. For Tree No. 2 this was 107 mph. The minimum wind speed to overturn the tree is calculated when the wind is going in the same direction as the tree lean. The minimum wind speed was 99 mph (Appendix H). The difference between the two critical wind speed values is 8 mph. For all other directions the difference will be less than 8 mph.

Step 2

The next step in calculating the probability that a tree will fall and reach a stream  $P(fs)$ , considering a period of time ( $n$ ) equal to 100 years, is to calculate the exceedance probability by using equation (11).

$$P(e) = 1 - \left( \frac{Tr-1}{Tr} \right)^n$$

As an example, consider the probability of wind coming from the North and exceeding the critical wind speed of 99 mph (Table 8) in a period of time equal to 100 years. This wind speed has a return interval of 450 years so:

$$P(e) = 1 - \left( \frac{450 - 1}{450} \right)^{100}$$

$$P(e) = 0.199.$$

This procedure is then repeated for each wind direction. The exceedance probability, wind direction probability and the probability the tree falls  $P(f)$  for each critical wind speed by each wind direction are shown in Table 9.

Table 9. Exceedance probability, wind direction probability and probability tree of fall  $P(f)$  during the next 100 years for each wind direction for Tree No. 2.

Wind Direction	Exceedance Probability $P(e)$	Wind Direction Probability $P(d)$	Probability Tree Falls, $P(f) = P(e) * P(d)$
N	0.199	0.017	0.0030
NNE	0.196	0.168	0.0330
NE	0.178	0.113	0.0200
ENE	0.147	0.000	0.0000
E	0.135	0.000	0.0000
ESE	0.118	0.000	0.0000
SE	0.106	0.000	0.0000
SSE	0.106	0.004	0.0004
S	0.118	0.411	0.0480
SSW	0.125	0.074	0.0090
SW	0.135	0.126	0.0170
WSW	0.156	0.013	0.0020
W	0.178	0.026	0.0050
WNW	0.196	0.017	0.0030
NW	0.199	0.030	0.0060
NWW	0.199	0.000	0.0000

### Step 3

The probability of a tree falling and reaching a stream  $P(fs)$ , requires a circular arc calculation. The circular arc is defined by the perpendicular downslope distance from the standing tree to the nearest channel boundary and tree height (Figure 18). For Tree No. 2, the tree height is 141 ft., the perpendicular distance from the tree to the stream is 51 ft, and the perpendicular distance azimuth is  $86^\circ$ . Thus, the angles  $a$  and  $b$  (Figure 19) equal  $68.8^\circ$  each. The circumference portion determined by the triangle ABC (Fig. 19) shows where the tree could fall and reach the stream. If the tree falls

between azimuth  $17.2^\circ$  ( $86^\circ - 68.8^\circ$ ) and  $148.8^\circ$  ( $86^\circ + 68.8^\circ$ ), it will reach the stream.

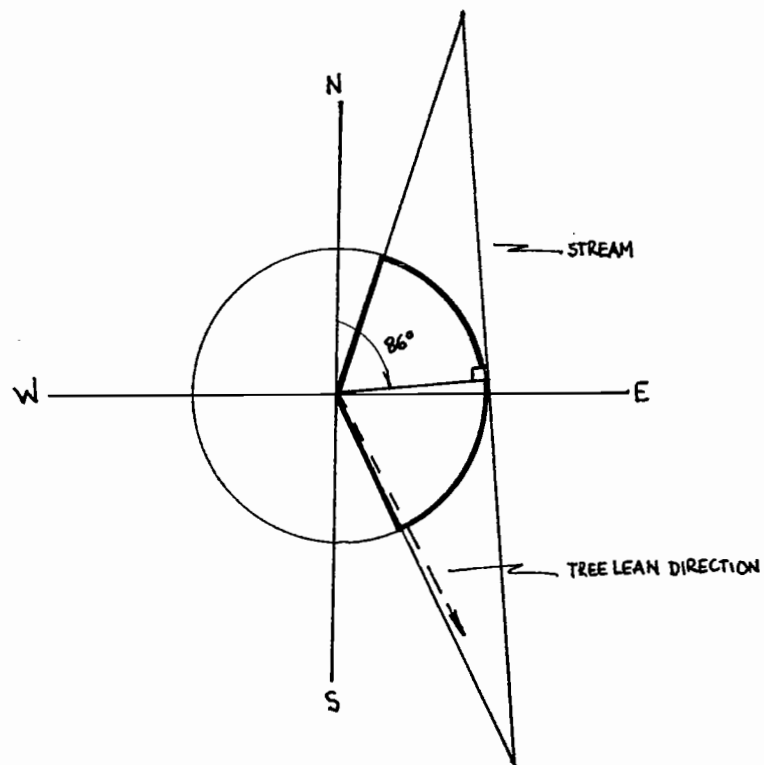


Figure 18. Circular arc diagram showing azimuth stream for Tree No. 2 and tree lean direction. The heavy line indicates the sector of a circle where a tree of sufficient height relative to its perpendicular slope distance from the stream could reach the stream if it fell.

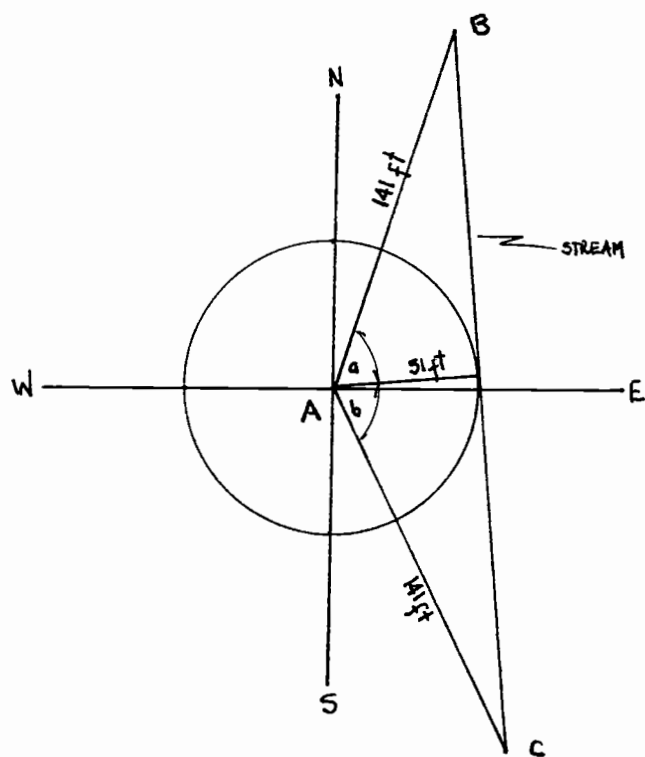


Figure 19. Relationship between perpendicular downslope distance from standing tree to nearest channel boundary and tree height for Tree No. 2.

The critical wind force for different wind directions for Tree No. 2 are shown in Table 10. The force due to gravity caused by the tree lean is equal to 1107 lbs. Table 11 shows the results for different wind directions and the resultant tree fall direction for Tree No. 2.

Table 10. Wind force (lbs) by wind direction for a critical wind for Tree No. 2.

N	NNE	NE	ENE	E	ESE	SE	SSE
7056	7199	7344	7638	7787	8089	8243	8243
S	SSW	SW	WSW	W	WNW	NW	NNW
8089	7937	7787	7490	7344	7199	7056	7056

Table 11. Tree fall direction by wind direction for Tree No. 2 considering moments due to critical wind force and tree lean. The critical zone for Tree No. 2 is  $17.2^{\circ}$  to  $148.8^{\circ}$ .

Wind direction	Wind force (lbs)	Tree fall direction (azimuth)	Will reach stream
N	7056	178	No
NNE	7199	199	No
NE	7344	221	No
ENE	7638	243	No
E	7787	266	No
ESE	8089	297	No
SE	8243	319	No
SSE	8243	340	No
S	8089	2	No
SSW	7937	26	Yes
SW	7787	49	Yes
WSW	7490	72	Yes
W	7344	94	Yes
WNW	7199	115	Yes
NW	7056	136	Yes
NNW	7056	157	No



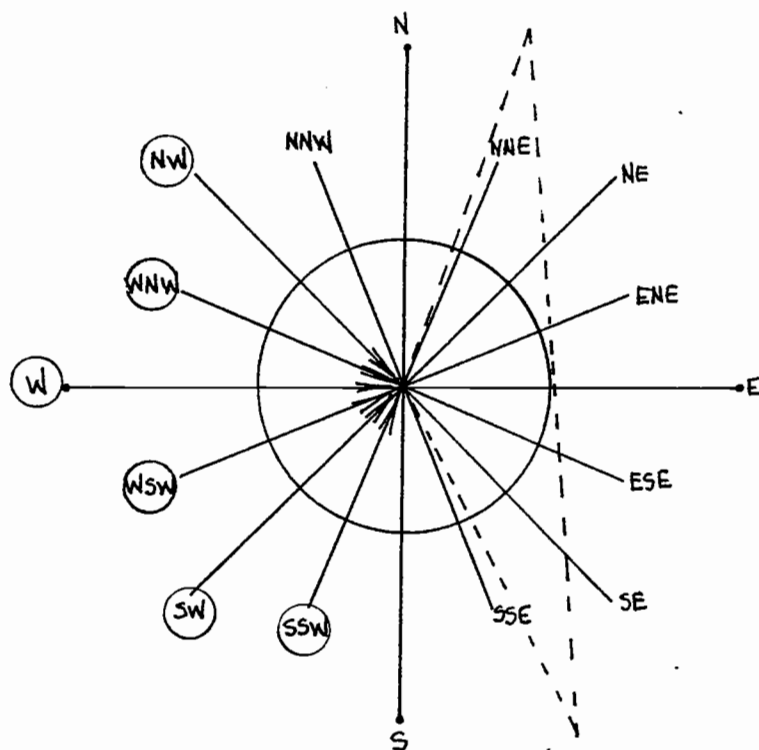


Figure 20. Standard wind rose diagram. The circled wind directions with arrows indicate wind directions which would push Tree No. 2 into the stream.

Using the Standard Wind Rose Diagram (Figure 20), we can represent the distribution of wind direction for sixteen possibilities. From Table 11, the wind directions that could result in a tree falling and reaching a stream are SSW, SW, WSW, W, WNW and NW.

#### Step 4

By using equation  $P(fs) = P(f) * P(s)$ , we can determine the probability of the tree falling and reaching the stream over a time period of 100 years. From Table 9 we take the probability the tree falls  $P(f)$  for each wind direction. For SSW, SW, WSW, W, WNW and NW) these probabilities are 0.009, 0.017, 0.002, 0.005, 0.003, and 0.006 respectively. Each  $P(f)$  value is then multiplied by  $P(s) = 1$  which represents the conditional probability where the standing tree has a height greater than its distance to the stream. These results are summarized in Figure 21. For example, for Tree No. 2, the critical wind speed to overturn this tree from the South is 106 mph. A wind of this speed from the South has a 4.8% probability of occurring during the next 100 years. However, even if this tree did fall it would not reach the stream.

Finally, the sum of the probabilities that Tree No. 2 could fall and reach the stream from each direction gives the total probability. In the case of Tree No. 2, there is a 4.2% probability that the tree will fall and reach a stream over a period of 100 years.

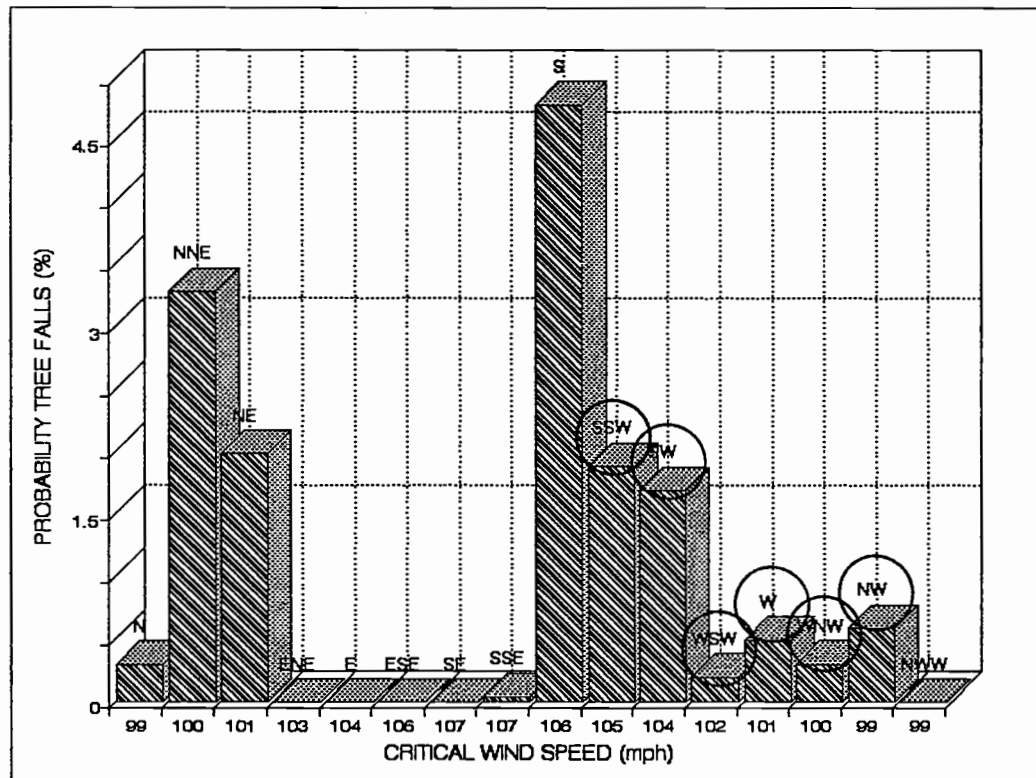


Figure 21. Relationship between probability that Tree No. 2 falls during the next 100 years and critical wind speed (mph). The wind directions that could blow a tree into the stream are circled.

### Simulation Process

To examine the sensitivity of critical wind speed to tree lean, a simulation was done for Tree No. 2. The maximum and minimum critical wind speed was calculated for the midpoint of each lean interval (Table 12). The difference between the maximum and minimum critical wind speed (mph) is shown in the last column of Table 12. This difference increases as the lean increases. For a large lean into the wind, a high wind speed will be necessary to counteract the natural tree lean.

Table 12. Results of tree lean simulation for Tree No. 2.

Lean Interval (%)	Maximum Critical Wind Speed ( $\alpha=180^\circ$ )	Minimum Critical Wind Speed ( $\alpha=0^\circ$ )	Difference in Critical Wind Speed (mph)
3	104	102	2
8	106	100	6
13	108	98	10
18	110	97	13
23	112	96	16
28	114	94	20
33	116	93	23
38	118	92	26
43	121	91	30
48	123	90	33
53	126	89	37
58	128	89	39
63	131	88	43
68	133	88	45

A graphic representation of maximum critical wind speed and minimum critical wind speed is shown in Figure 22. The difference between both values is represented in Figure 23.

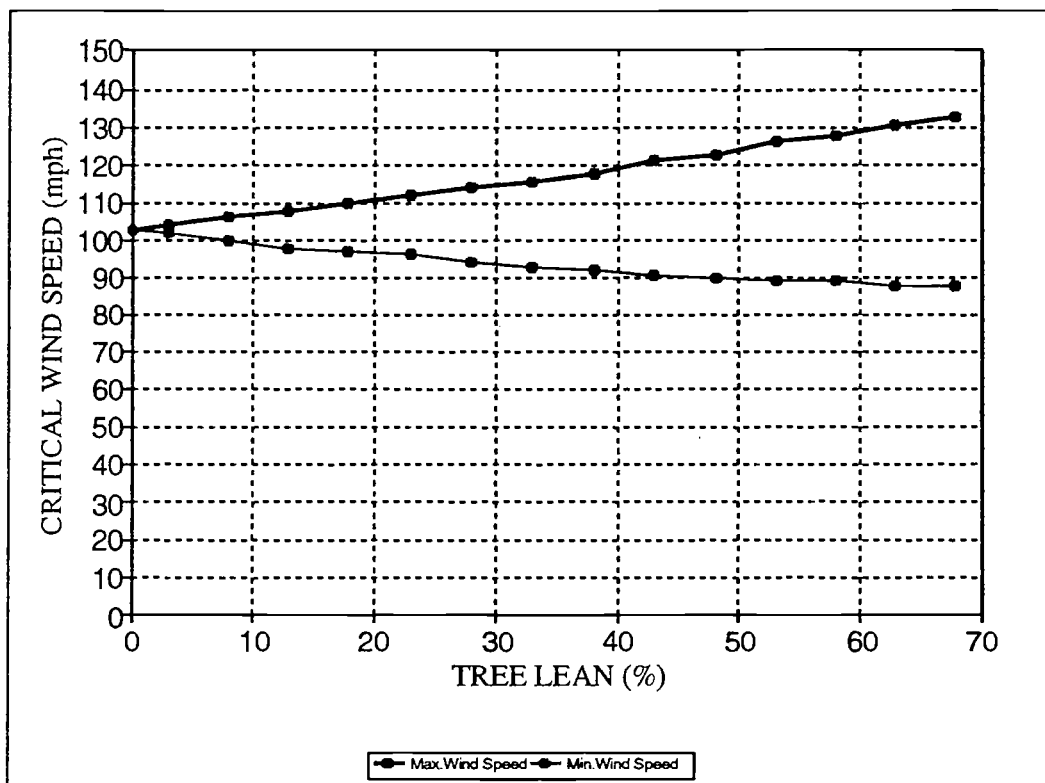


Figure 22. Relationship between tree lean (%) and maximum and minimum critical wind speed (mph) for Tree No. 2.

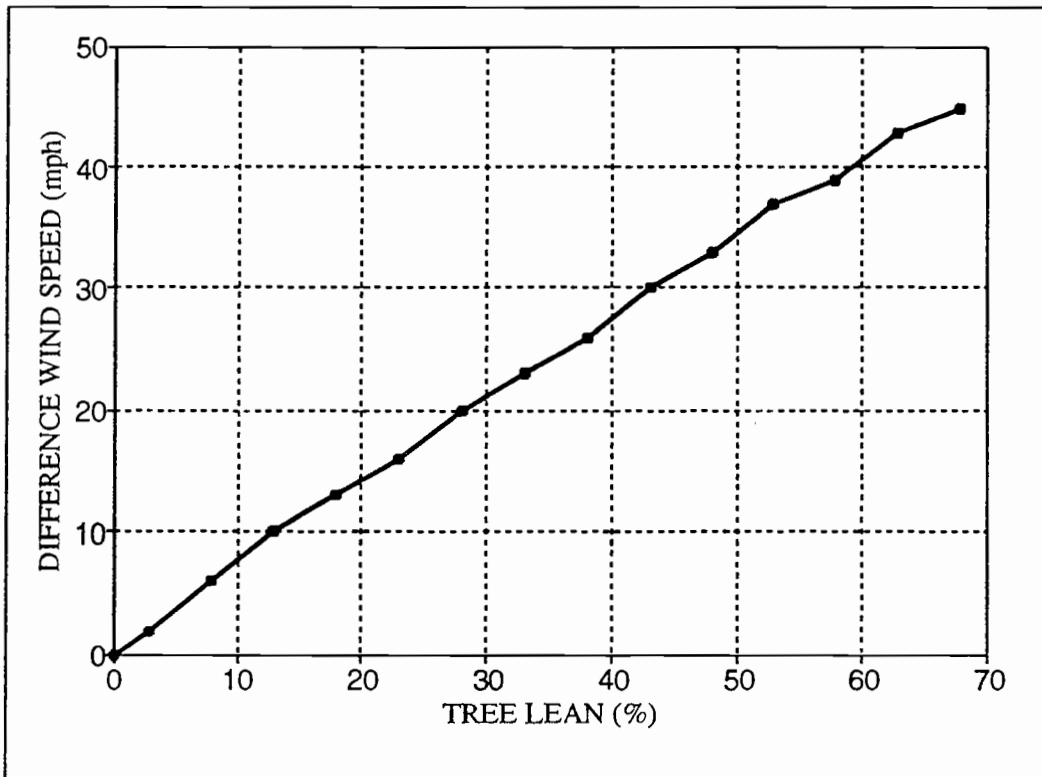


Figure 23. Relationship between tree lean (%) and the difference in maximum and minimum critical wind speed (mph) for Tree No. 2.

## DISCUSSION

Field Data

Observations by others (Conway 1973) have indicated that trees lean downhill. It was thought that the tendency to lean downhill might be caused by heavier crown development on the downhill side of the tree due to the greater amount of light available to that side of the tree, by soil creep, or some other factor. A significant linear correlation was found between lean and slope although there was considerable scatter. In general, the steeper the slope, the greater the tree lean downhill. When tree lean data was stratified by aspect, the linear correlation was higher for the NE and SW aspects, slightly weaker for the NW aspect and not correlated for the SE aspect.

A linear model relating tree lean to ground slope appeared appropriate from tests of the regression line intercepts and coefficients and examination of residuals. Some measurement bias may exist as field measurements were concentrated in the first six feet of the tree. This may have not been representative of the overall tree lean, although it appeared so for the trees measured in this study.

### Physical Model

The physical model developed in this project considers an individual tree facing the wind. The forces acting to overturn the tree are wind and gravitational force associated with tree lean. Resistance to overturning is provided by the root system. A wind velocity necessary to overcome the estimated strength of the root system is calculated for each wind direction. The wind velocity, defined as the critical wind velocity, differs by direction based upon the lean of the tree. The critical wind velocities calculated in this study for winds which blow in the direction of the lean are probably overestimated for three reasons. First, this model does not consider the increasing overturning moment due to the tree weight as the tree is deflected by the wind. Second, the crown of the tree is assumed symmetrical. That is, the center of mass of the crown is assumed to lie along the axis of the tree. If the tree crown is not symmetrical, the center of mass of the crown will probably lie on the downhill side of the tree axis, increasing the overturning moment toward the downhill side. No research has been found describing the center of mass of the tree crown as a function of ground slope. Third, the assumed resisting moment of the roots uses average root strength relationships derived from a linear fit on test data by Fraser (1962). Trees with root strength lower than the average (for example, caused by root rot) would be



the first to fail and would fail at wind velocities lower than the critical wind velocities calculated in this paper. Since the literature by Fraser did not provide the raw data, nor confidence limits for the data, the variability of his data is not known.

On the other hand, the wind force has been assumed to occur at the center of force on the crown with a force equal to that caused by a wind above tree top level. This approach has been assumed by some other researchers (Petty and Swain 1985) although it is known that wind velocity is not constant, but decreases at crown level and continues to decrease in the lower crown. To the extent that the wind in the crown is not as high as the above crown wind, the wind force is being overestimated. More accurate estimates of the wind force might be made by integrating along an assumed wind profile as a function of crown height. This preliminary study, however, provides an initial attempt to link the factors of wind, tree crown, tree lean, and root resistance in a physical model.

#### Probabilistic Model

A probabilistic model has been developed to estimate the probability of a wind occurring from a specified direction with a velocity high enough to overturn the tree. The probability of the tree falling in a stream was developed by adding the probabilities of the applicable critical wind speed

from each direction and considering tree height, and the location from the stream. This method differs from existing models which assume the probability of a tree falling in the stream is a function only of its height and its location with respect to the stream. Robison and Beschta (1990) note in their model development for coarse woody debris, that although they did not include ground slope in their model, that it probably plays a role. They note that in field observations that 75 percent of the trees laying on the ground had fallen downslope on gradients ranging from 17 to 70 percent. Information on tree lean and storm wind direction were not known. In this study we postulate that wind direction and center of tree mass are important variables. The assumption of the center of tree mass being located along the axis of the bole may be conservative. To the extent that the center of tree mass, particularly the crown lies to the downhill side of the tree, the lower the critical wind speed necessary to overturn the tree and the more likely the tree is to fall downhill. As better information on the center of tree mass of trees on slopes becomes available, it can easily be incorporated into models of this type.

The wind data is approximate at best. Not only was a limited period of data available, which did not facilitate estimating the frequency of extreme events, but the complexities of wind direction and speed in mountainous terrain have not been considered. Nevertheless, a methodology

for incorporating wind direction and velocity probabilities has been developed in this study which can serve as a basis for subsequent research to improve upon.

#### Model Validation

Current riparian management guidelines to promote coarse woody debris do not consider wind direction. To the extent that some riparian lands may be needlessly withdrawn from the timber base, individuals and society may be forgoing benefits from timber production. However, the physical and probabilistic models in this project need to be tested. This will not be an easy or short-term task. One test would be to periodically monitor the two sample areas before and after wind events to assess initial conditions and subsequent tree damage. All trees measured in this study have been identified with tags and the study areas lie within stands that are reserved from treatment in the Research Forest Plan unless a catastrophic event occurs.

#### Model Application

The objective for developing this model was to illustrate a methodology for linking the physical elements of (a) tree location and geometry and (b) wind velocity, direction and probability of occurrence to estimate the probability of a

tree falling into a stream. Detailed calculations have been shown for an individual tree; Tree No. 2 from Area A. Eventually, if this model or a derivative of it, is validated, it may provide a means for predicting coarse woody debris delivery to streams from buffer strips. For example, the model could predict which trees are unlikely to fall into the stream. These trees, unless more valuable for uses other than for timber production, could be designated for removal for harvest. Because wind and tree interaction with adjacent trees in stands were not considered in model development, this model would not be appropriate for application in stands or in wide buffer strips. The model might also be useful in analyzing isolated trees left after harvest for wildlife or other purposes.

## CONCLUSIONS AND FUTURE WORK

The measurement of 200 conifers along two creeks located in McDonald Forest found that tree lean varied from 1 to 34 (uphill) percent and from 1 to 29 (downhill) percent on slopes of 1 to 88 percent. Approximately 75 percent of the trees leaned downhill and 25 percent of the trees leaned uphill. A significant linear relationship was found between lean and slope although there was considerable scatter. In general, the steeper the slope, the greater the tree lean downhill. When tree lean data was stratified by aspect, the linear relationship between lean and slope was higher for the NE and SW aspects, slightly weaker for the NW aspect and not related for the SE aspect.

A physical and probabilistic model was developed to calculate the critical wind speed of the tree for each wind direction and to estimate the probability of a tree falling toward the stream during a specified period of time.

By considering the maximum and minimum critical wind speed of the tree, it is possible to estimate the importance of the tree lean and its direction and probability of fall. If the difference between maximum and minimum wind speed is low, then the tree lean will not have an important effect on tree fall.

In this study, the difference between maximum and minimum

critical wind speed was 8 mph for Tree No. 2. Most trees on the areas studied had a similar lean. Using a computer simulation, lean values were varied from 3 to 68 percent. Analysis showed that tree lean greater than 60 percent created differences in critical wind speed above 40 mph.

The physical model represents only a preliminary investigation of the effect of tree lean and wind in delivering coarse woody debris to streams. The wind speed required to overturn a tree for a given root strength is probably being overestimated because the induced moment caused by the tree weight as the tree is being pushed by the wind is not considered. If resistance of the root system could be expressed as a function of the angle of rotation of the bole at ground level, as has been suggested by Pyles (1987), the tree could be modeled as a tapered column with a non-fixed base. Numerical procedures for solving this problem, including the induced moment, have been presented by Sessions (1984). This approach would provide estimates of tree deflection along the bole and the resulting moment at the base. Such an approach could also provide estimates of the combined stress along the bole and would give indications of whether the tree would overturn or snap under wind action.

Additionally, future work might also include effects of changes of tree diameter, height and crown in the mathematical and probabilistic model. This mathematical and probabilistic model assumes a mature tree which does not grow and evaluates

the probability of a critical wind occurring within a specified planning horizon. If changes in tree height were considered, trees currently not tall enough to reach the stream, might grow tall enough to reach the stream during the planning horizon.

Increased understanding of root strength with age and disease is also needed. In this study, root strength did not consider biological or pathological agents. All trees which do not burn eventually die and fall. Trees which have survived for long periods of time have been observed falling under conditions of little or no wind.

In conclusion, this study must be considered only an initial step toward developing an understanding of coarse windy debris delivery to streams. Much remains to be done.

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APPENDICES

## Appendix A. Data Form

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Date: \_\_\_\_\_

Area: \_\_\_\_\_

Tree N°: \_\_\_\_\_

Percent Lean: \_\_\_\_\_

dbh (inch): \_\_\_\_\_

Slope (to stream) (%): \_\_\_\_\_

Height (ft): \_\_\_\_\_

Perpendicular Distance to Stream (ft): \_\_\_\_\_

Lean Distance to Stream (ft): \_\_\_\_\_

Angle to Stream (az): \_\_\_\_\_

Angle to Lean (az): \_\_\_\_\_

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Comments:

## Appendix B

Table B1: Data Base Area A

Tree Number	Dbh (inch)	Height (feet)	Volume (cu.feet)	Per.Dist. Stream (feet)	Slope Stream (%)		Angle Stream (az)		Lean Tree (%)	Lean Dist. Stream (feet)		Slope Lean (%)		Angle Lean (az)		Aspect (az)
1	26	101	121.4	26	-36	106	4	59	-35	142	142					
2	28	141	205.9	51	-30	86	11	105	25	152	120					
3	23	134	133.4	72	-48	98	6	44	-53	140	140					
4	23	130	133.4	106	-51	110	8	205	-56	140	128					
5	25	110	126.7	117	-46	110	17	210	-52	144	148					
6	12	105	34.8	111	-51	106	11	118	-51	125	134					
7	28	107	154.7	147	-49	126	11	out	-50	182	143					
8	10	68	14.8	153	-49	126	13	out	-50	182	143					
9	17	115	71.2	104	-55	122	6	out	55	334	166					
10	22	127	123.3	95	-58	110	6	out	55	336	156					
12	12	74	20.5	174	-45	264	7	184	-45	276	254					
13	21	135	124.2	143	-42	260	14	166	-40	240	278					
14	22	140	134.8	127	-47	261	12	132	-47	268	267					
15	16	115	64.0	117	-45	262	5	121	-40	267	262					
16	37	131	307.7	149	-41	248	8	157	-45	274	281					
17	25	117	140.0	150	-42	247	18	151	-41	309	275					
18	14	92	36.0	137	-40	284	20	146	-43	250	292					
19	25	140	168.7	121	-45	237	10	133	-50	290	280					
20	10	75	17.3	115	-46	240	3	136	-51	282	298					
21	8	67	11.7	113	-45	244	3	138	-53	292	294					
22	28	127	188.4	106	-44	242	13	129	-51	302	280					
23	17	118	71.2	78	-48	242	12	112	-44	309	276					
24	19	136	104.2	72	-32	224	9	71	-40	276	253					
25	17	124	71.2	55	-44	234	3	out	-45	94	232					



Table B2: Data Base Area A

Tree Number	Dbh (inch)	Height (feet)	Volume (cu.feet)	Per.Dist. Stream (feet)	Slope Stream (%)	Angle Stream (az)	Lean Tree (%)	Lean Dist. Stream (feet)	Slope Lean (%)	Angle Lean (az)	Aspect (az)
26	29	165	276.7	49	-49	334	8	51	-47	255	244
27	12	100	31.1	76	-35	230	8	90	-28	296	254
28	12	95	31.1	73	-27	224	10	69	33	234	261
29	27	146	209.8	87	-29	228	13	84	-33	254	256
30	55	212	1096.5	187	-64	315	12	195	-67	298	289
31	64	230	1579.5	154	-74	308	7	161	-76	291	290
32	15	111	51.5	115	-47	305	7	118	-48	294	286
33	14	115	50.6	114	-52	290	5	out	60	107	318
34	22	145	146.5	104	-67	297	7	out	-22	57	286
35	33	148	298.4	8	-58	320	16	9	-70	268	287
36	25	125	154.4	164	-90	112	1	166	-88	142	125
37	38	140	352.1	86	-53	102	8	100	-48	157	142
38	37	155	394.2	76	-54	114	5	77	-55	118	138
39	28	140	205.9	29	-54	110	9	39	-52	168	138
40	14	105	45.6	26	50	84	29	29	-43	115	136
41	36	150	347.7	125	-54	118	15	120	-55	141	140
42	12	52	14.1	52	-60	112	3	50	-60	124	132
43	31	163	289.0	198	-57	225	5	206	-58	122	100
44	47	139	460.1	188	-62	112	5	198	-62	124	105
45	12	65	20.5	50	45	117	20	52	-46	123	140
46	14	108	40.7	193	-75	320	9	195	-71	307	318
47	17	116	71.2	189	-66	298	20	out	-20	218	319
48	35	180	412.2	170	65	312	9	150	-30	252	319
49	32	140	260.3	149	-62	290	20	144	-60	280	310
50	65	190	1283.9	120	-68	302	15	127	-67	286	308

Table B3: Data Base Area A

Tree Number	Dbh (inch)	Height (feet)	Volume (cu.feet)	Per.Dist. Stream (feet)	Slope Stream (%)	Angle Stream (az)	Lean Tree (%)	Lean Dist. Stream (feet)	Slope Lean (%)	Angle Lean (az)	Aspect (az)
51	14	76	31.4	115	-55	291	6	119	-60	298	312
52	50	195	837.7	94	-58	297	20	109	-53	321	300
53	38	180	476.1	95	-65	294	17	97	-67	285	304
54	14	80	31.4	87	-62	302	10	114	-63	300	285
55	32	174	328.8	56	-50	340	10	58	-60	392	340
56	19	88	61.7	125	-64	385	18	out	50	173	318
57	60	206	1232.3	94	-60	278	12	96	-61	278	262
58	23	151	158.4	191	-50	290	19	195	-57	271	265
59	49	220	937.9	99	-53	273	10	151	-45	322	292
60	47	185	704.8	125	-43	288	6	120	-38	248	274
61	33	125	251.6	114	-47	289	20	115	-36	254	297
62	18	114	71.0	113	-43	275	22	157	-35	325	290
63	32	148	282.7	104	-51	270	2	110	-53	308	316
64	48	178	697.5	100	-49	280	4	110	-55	297	320
65	47	190	728.2	199	-55	134	5	189	-50	110	122
66	47	182	690.9	168	-45	139	2	157	-47	120	100
67	40	190	556.2	143	-60	131	16	151	-45	95	150
68	27	156	226.8	96	-55	133	5	100	-56	148	140
69	40	180	520.9	133	-68	122	10	143	-70	105	110

Appendix C

Table C1: Data Base Area B

Tree Number	Dbh (inch)	Height (feet)	Volume (cu.feet)	PerDist. Stream (feet)	Slope Stream (%)		Angle Stream (az)		Lean Stream (feet)		Slope Lean (%)		Angle Lean (az)		Aspect (az)
70	24	133	143.7	32	-47	173	11	29	-45	192	210				
71	32	155	305.5	65	-48	182	17	69	-48	203	216				
72	15	127	63.0	72	-41	175	9	140	-40	215	192				
73	35	145	330.9	84	-45	177	13	138	-37	232	204				
74	15	80	35.5	87	-45	177	34	out	29	55	204				
75	14	112	45.6	129	-25	194	5	out	27	70	228				
76	25	127	154.4	196	-47	236	10	282	-38	282	245				
77	34	139	289.6	198	-47	236	9	out	9	28	257				
78	31	132	225.4	200	-47	230	13	out	9	90	257				
79	58	216	1231.1	52	-80	20	18	86	-60	310	352				
80	48	236	986.7	53	-65	12	5	54	-65	359	341				
81	51	240	1119.9	57	-55	360	14	out	18	272	341				
82	44	204	590.2	57	-55	360	17	out	-2	124	358				
83	27	125	176.8	65	-15	12	12	out	5	188	344				
84	45	152	514.0	93	-15	32	15	out	-32	292	334				
85	50	213	933.7	95	-19	22	7	out	10	165	324				
86	60	242	1502.5	129	-42	2	15	out	24	240	334				
87	37	150	364.8	199	-68	254	13	200	-68	16	3				
88	30	148	252.4	120	-35	184	11	out	-12	292	224				
89	25	138	168.7	127	-30	174	2	out	15	50	220				
90	21	136	124.2	125	-30	200	5	142	-34	172	206				
91	28	126	188.4	112	-20	182	6	114	-20	200	216				
92	21	123	103.3	164	-14	184	9	out	3	110	220				
93	13	80	27.5	138	-19	188	6	175	-20	226	203				
94	14	96	40.7	154	-10	179	13	out	9	48	210				
95	22	150	146.5	170	-10	177	8	out	8	45	218				

Table C2: Data Base Area B

Tree Number	Dbh (inch)	Height (feet)	Volume (cu.feet)	Per.Dist. Stream (feet)	Slope Stream (%)		Angle Stream (az)		Lean Tree (%)		Lean Stream (feet)		Slope Lean (%)		Angle Lean (az)		Aspect (az)
96	69	266	2155.3	29	-44	238	6	238	6	34	-43	284	308				
97	66	244	1792.6	31	-37	252	14	252	14	out	-19	74	302				
98	34	178	391.8	70	-25	270	19	270	19	out	-7	173	315				
99	42	168	514.5	75	-29	264	10	264	10	out	16	80	289				
100	40	204	591.9	96	-25	260	9	260	9	198	-15	321	292				
101	33	200	422.8	96	-20	262	11	262	11	out	10	148	306				
102	13	87	31.6	117	-28	230	1	230	1	out	30	66	278				
103	36	145	347.7	132	-37	260	15	260	15	out	18	50	281				
104	49	200	834.1	162	-40	272	6	272	6	160	-40	250	268				
105	25	145	183.3	193	-40	250	7	250	7	218	-42	278	248				
106	51	220	1005.8	23	-28	80	10	80	10	out	10	248	54				
107	37	210	542.3	27	-33	86	12	86	12	out	22	216	64				
108	52	240	1158.5	34	-39	100	8	100	8	out	20	270	57				
109	48	222	914.9	51	-36	102	10	102	10	out	14	236	64				
110	49	216	916.9	77	-34	72	5	72	5	out	-10	342	45				
111	26	140	180.8	114	-28	64	12	64	12	out	15	174	47				
112	58	240	1401.8	104	-35	64	7	64	7	out	-2	160	75				
113	15	119	57.2	95	-34	74	8	74	8	out	30	264	48				
114	56	235	1284.6	86	-73	98	11	98	11	94	-65	58	81				
115	63	220	1454.9	74	-52	77	1	77	1	75	-50	76	80				
116	66	195	1361.2	44	-30	105	2	105	2	50	-31	120	77				
117	45	225	831.1	10	-43	98	3	98	3	12	41	118	70				
118	33	175	371.9	151	-44	70	3	70	3	154	-42	90	100				
119	62	210	1336.2	11	-62	278	8	278	8	16	-27	236	308				
120	40	174	486.1	124	-73	282	9	282	9	179	-65	318	320				
121	24	170	198.6	137	-53	292	13	292	13	140	-54	290	317				

Table C3: Data Base Area B

Tree Number	Dbh (inch)	Height (feet)	Volume (cu.feet)	Per.Dist. Stream (feet)	Slope Stream (%)	Angle Stream (az)	Lean Tree (%)	Lean Dist. Stream (feet)	Slope Lean (%)	Angle Lean (az)	Aspect (az)
122	22	145	146.5	148	-55	285	5	206	-58	326	308
123	36	189	462.5	162	-50	272	6	172	-52	285	306
124	27	173	244.1	168	-57	287	9	230	-55	315	302
125	30	160	272.9	172	-54	297	10	out	-12	12	302
126	18	158	111.5	182	-35	290	7	out	-9	216	320
127	39	185	532.0	189	-49	306	7	200	-50	294	300
128	52	243	1176.4	42	-75	285	4	40	-74	267	307
129	52	238	1146.6	47	-71	268	7	out	12	38	300
130	38	160	413.0	52	-71	260	9	out	50	105	290
131	46	209	788.5	55	-62	270	14	60	-70	301	302
132	46	236	916.1	67	-62	264	9	out	13	60	295
133	22	156	158.4	67	-50	261	14	69	-51	272	297
134	38	225	618.2	71	-54	257	6	out	-34	104	298
135	21	107	93.2	134	-51	266	14	out	-42	329	294
136	27	108	145.1	169	-51	263	12	261	-53	298	298
137	23	166	184.4	159	-38	174	7	out	1	46	298
138	35	150	330.9	179	-38	276	9	out	-16	216	290
139	13	114	40.1	183	-29	268	10	out	15	58	292
140	25	150	183.3	186	-36	278	9	195	-39	312	374
141	26	155	212.3	195	-37	295	3	200	-36	287	315
142	13	98	35.8	200	-32	280	8	out	24	98	328
143	14	127	55.8	169	-40	282	11	out	-16	368	310
144	22	139	134.8	157	-40	271	8	228	-27	232	296
145	26	150	196.4	157	-36	277	11	160	-36	278	306
146	51	190	840.0	134	-68	68	16	132	-67	86	62
147	57	225	1255.8	140	-62	62	4	out	-42	232	73

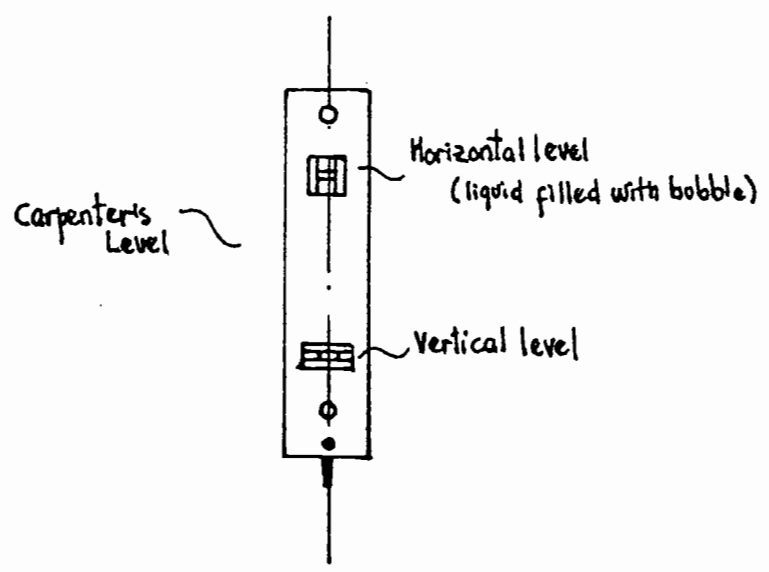
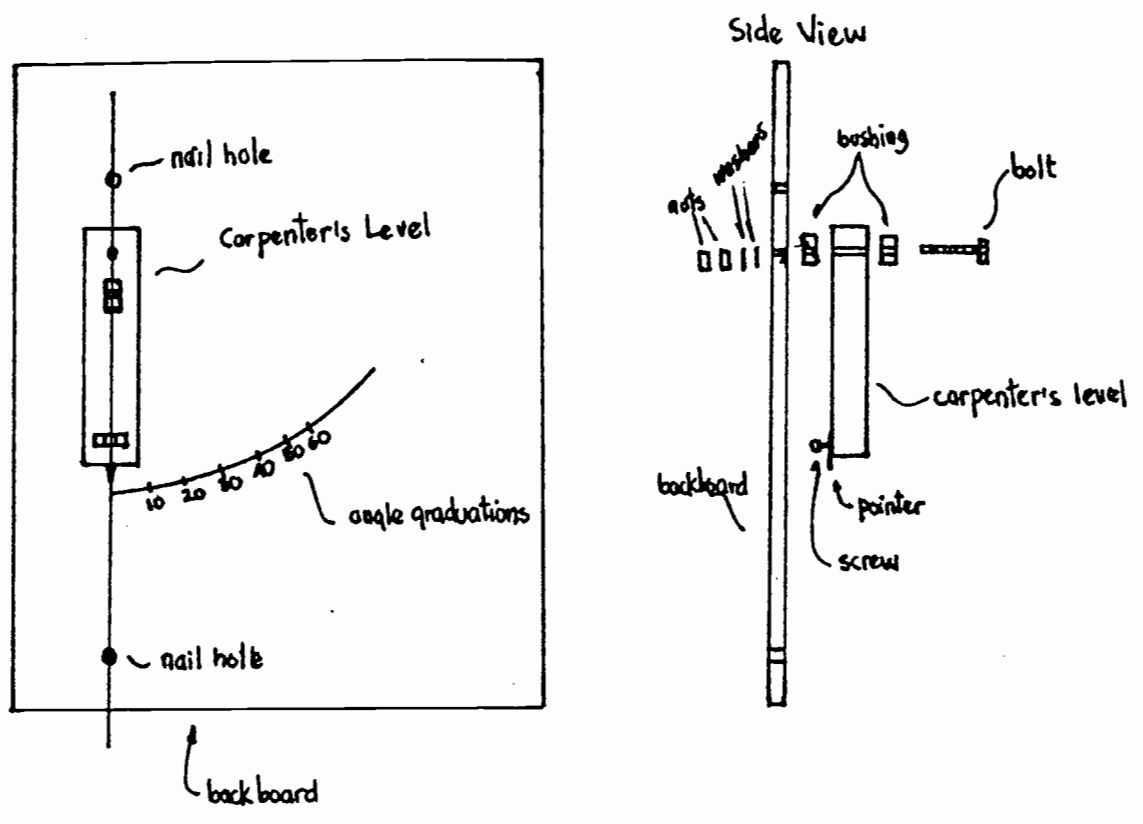
Table C4: Data Base Area B

Tree Number	Dbh (inch)	Height (feet)	Volume (cu.feet)	Per.Dist. Stream (feet)	Slope Stream (%)	Angle Stream (az)	Lean Tree (%)	Lean Stream (feet)	Slope Lean (%)	Angle Lean (az)	Aspect (az)
148	46	195	724.0	166	-55	58	9	167	-56	60	60
149	52	195	897.1	194	-42	67	15	200	-45	99	64
150	51	128	520.6	41	-29	218	19	53	-23	238	267
151	28	137	205.9	27	-10	187	5	53	3	146	244
152	11	73	17.6	20	-11	186	7	51	-12	247	273
153	25	114	126.7	58	-15	202	2	out	20	66	282
154	11	95	26.6	94	-10	195	4	out	12	69	260
155	12	104	31.1	93	-8	197	1	94	-8	198	269
156	19	120	86.6	96	-10	211	6	out	-24	304	262
157	13	92	31.6	100	-5	198	6	out	-17	334	267
158	14	90	36.0	134	-2	194	4	out	26	92	318
159	27	145	209.8	185	-10	96	12	out	20	149	284
160	25	168	213.3	190	-8	204	6	out	-31	280	306
161	15	50	21.0	192	-8	193	8	out	-31	278	260
162	39	151	400.1	198	-10	197	4	out	-8	246	272
163	59	169	939.7	140	-16	202	6	out	-34	254	282
164	47	213	838.0	31	-52	251	9	33	-50	236	286
165	22	116	101.1	35	-45	229	8	36	-47	270	280
166	36	172	424.0	150	-50	294	3	out	22	185	348
167	31	183	333.3	170	-34	289	11	175	-32	284	349
168	28	153	223.7	186	-33	291	10	188	-34	290	327
169	36	265	689.8	33	-50	23	18	35	-55	256	348
170	22	158	158.4	68	-60	364	7	70	-60	374	373
171	11	102	26.6	85	-45	358	9	86	-50	370	360
172	48	194	775.1	116	-45	357	9	142	-46	350	8
173	11	88	23.5	129	-50	8	10	130	-50	253	370

Table C5: Data Base Area B

Tree Number	Dbh (inch)	Height (feet)	Volume (cu.feet)	Per.Dist. Stream (feet)	Slope Stream (%)	Angle Stream (az)	Lean Tree (%)	Lean Stream (feet)	Slope Lean (%)	Angle Lean (az)	Aspect (az)
174	25	96	113.3	134	-50	21	4	out	40	219	17
175	32	168	328.8	136	-50	273	20	out	-26	6	19
176	19	88	61.7	139	-51	13	13	149	-52	252	15
177	58	162	866.3	22	-54	182	10	out	-42	30	218
178	31	171	311.0	36	-43	207	8	58	-30	256	233
179	19	114	78.1	41	-45	201	5	out	5	320	234
180	28	156	241.8	73	-38	212	5	75	-38	223	228
181	25	113	126.7	92	-38	218	20	167	-34	262	226
182	33	158	322.5	95	-43	202	9	97	-47	214	236
183	12	76	20.5	99	-36	197	3	105	-32	226	222
184	14	119	50.6	107	-38	297	7	117	-38	217	236
185	36	148	347.7	192	-40	232	7	249	-42	250	221
186	21	120	103.3	197	-37	214	10	out	22	68	231
187	13	98	35.8	192	-25	215	7	194	-25	233	206
188	27	163	226.8	27	-30	366	21	30	-12	46	334
189	56	220	1184.3	14	-55	353	11	22	-17	77	336
190	56	230	1251.0	23	-30	24	6	32	-16	88	14
191	77	272	2682.9	57	-41	8	5	out	-24	162	322
192	65	190	1283.9	117	-57	7	3	out	10	136	350
193	53	232	1148.5	65	-58	9	1	67	-58	2	27
194	48	238	997.1	101	-68	20	6	out	5	265	360
195	46	235	911.3	104	-61	2	20	103	-61	22	6
196	47	232	931.3	111	-61	20	9	out	27	189	358
197	48	160	612.5	163	-72	30	13	223	-57	347	13
198	43	190	623.3	182	-70	26	11	184	-70	38	32
199	37	150	364.8	194	-47	36	16	388	-42	336	358
200	36	163	375.7	200	-45	33	5	236	-25	65	18

Appendix D. Lean Measuring Device (LMD)





Appendix E. Maximum Moment Calculations by Fraser, Stoupa and Pestal equations.

Given DBH = 10 inches

a) FRASER

$$MM = -4270 + 73.58 * Wt \text{ (lb-ft)}$$

$$Wt = 49 \text{ lb/ft}^3 * 14.5 \text{ ft}^3 = 710.5 \text{ lb}$$

$$MM = -4270 + 73.58 * 710.5 = 48009 \text{ lb-ft}$$

b) STOUPA

$$\text{Ultimate Load on Stump} = 260.19 (\text{DBH})^{1.99} \text{ (lb)}$$

$$= 25427 \text{ lbs}$$

$$\text{Depth to point of rotation} = 2.19 (\text{DBH})^{1.28} \text{ (inches)}$$

$$= 41.73 \text{ inches} = 3.48 \text{ ft} + 1 \text{ ft}$$

then

$$MM = 25427 \text{ lb} * 4.48 \text{ ft} = 113913 \text{ lb-ft}$$

c) PESTAL

$$\text{Maximum possible tension: } S_{max} = \frac{D^2}{3}$$

$$\text{DBH} = 10 \text{ inches} = 25.4 \text{ cm} = 0.254 \text{ m} * 10 = 2.54 \text{ decimeters}$$

then

$$S_{max} = 2.15 \text{ tons} = 4370 \text{ lbs.}$$

$$MM = 4730 \text{ lb} * 4.48 \text{ ft.} = 21190 \text{ lb-ft.}$$

## Appendix F. Derivation of the Critical Wind Speed Equation.

From Figure 6 (page 27) we have:

Let:

$$WT = Wt(\sin\beta \cdot e_1 - \cos\beta \cdot e_3)$$

$$KT = K1(\cos\alpha \cdot e_a + \sin\alpha \cdot e_b)$$

$$= K1[\cos\alpha(e_1 \cdot \cos\beta + e_3 \cdot \sin\beta) + \sin\alpha \cdot e_2]$$

$$MM = Hw \cdot e_3 \times WT + Hc \cdot e_3 \times KT$$

$$\begin{aligned} MM &= Hw \cdot e_3 \times [Wt(\sin\beta \cdot e_1 - \cos\beta \cdot e_3)] + \\ &\quad + Hc \cdot e_3 \times K1[\cos\alpha(e_1 \cdot \cos\beta + e_3 \cdot \sin\beta) + \sin\alpha \cdot e_2] \\ &= Wt \cdot Hw \cdot \sin\beta \cdot e_2 + K1 \cdot Hc \cdot [\cos\alpha \cdot \cos\beta \cdot e_2 - \sin\alpha \cdot e_1] \\ &= -K1 \cdot Hc \cdot \sin\alpha \cdot e_1 + (K1 \cdot Hc \cdot \cos\alpha \cdot \cos\beta + Wt \cdot Hw \cdot \sin\beta) \cdot e_2 \end{aligned}$$

then

$$MM = \sqrt{(K1 \cdot Hc \cdot \sin\alpha)^2 + (K1 \cdot Hc \cdot \cos\alpha \cdot \cos\beta + Wt \cdot Hw \cdot \sin\beta)^2} \quad (a)$$

Finally, if we substitute  $K1 = 1/2 \cdot \rho l / g \cdot Cd \cdot u^2 \cdot Ac$  into equation (a) and solve the quadratic equation for "u" after some algebraic manipulation we can express

$$u = \sqrt{\frac{A \pm B}{C}}$$

where

$$A = -Wt \cdot Hw \cdot \cos\alpha \cdot \cos\beta \cdot \sin\beta$$

$$\begin{aligned} B &= [(Wt \cdot Hw \cdot \cos\alpha \cdot \cos\beta \cdot \sin\beta)^2 - \\ &\quad - (\sin^2\alpha + \cos^2\alpha \cdot \cos^2\beta) \cdot \\ &\quad \cdot (Wt^2 \cdot Hw^2 \cdot \sin^2\beta - MM^2)]^{1/2} \end{aligned}$$

$$C = 1/2 \cdot \rho l / g \cdot Cd \cdot Ac \cdot Hc \cdot (\sin^2\alpha + \cos^2\alpha \cdot \cos^2\beta)$$

Appendix G. Wind: Percentage Frequency by Direction for  
Corvallis, Oregon.

MPH	N	NNE	NE	ENE	E	ESE	SE	SSE
CALM								
4-15	4.6	3.6	4.6	0.3	1.7	0.4	2.0	2.7
16-31	0.4	3.9	2.6	-	-	-	-	0.1
32-47	-	-	-	-	-	-	-	-
47 <sup>+</sup>	-	-	-	-	-	-	-	-
TOTAL	5.0	7.5	7.2	0.3	1.7	0.4	2.0	2.8
Percentage (*)	1.7	16.8	11.3	0.0	0.0	0.0	0.0	0.4
MPH	S	SSW	SW	WSW	W	WNW	NW	NNW
CALM								
4-15	11.5	3.6	3.5	1.9	4.7	2.9	6.6	2.3
16-31	9.5	1.7	2.9	0.3	0.6	0.4	0.7	-
32-47	-	-	-	-	-	-	-	-
47 <sup>+</sup>	-	-	-	-	-	-	-	-
TOTAL	21.0	5.3	6.4	2.2	5.3	3.3	7.3	2.3
Percentage (*)	41.1	7.4	12.6	1.3	2.6	1.7	3.0	0.0
TOTAL CALM: 19.8								

Total Percentage Frequency by Directions: 99.8

Note: (\*) Percentages calculated from winds  $\geq$  16 mph.

Appendix H. Maximum and Minimum Critical Wind Speed  
Calculation.

Statistics for Tree Number 2, Area A.

DBH (in.)	Height (feet)	Volume (ft <sup>3</sup> )	Per.distance to stream (feet)	Lean distance to stream (feet)	Angle stream (az)	Tree lean (deg.)
28	141	205.9	51	105	86	6.3

Maximum Moment Calculation

Let:  $Wt = \text{Density} * \text{Volume}$

$$Wt = 49 \text{ lb/ft}^3 * 205.9 \text{ ft}^3$$

$$Wt = 10089 \text{ lbs.}$$

Then

$$MM = -4270 + 73.58 * Wt$$

$$MM = 738086 \text{ lb-ft}$$

Crown Cross Sectional Area Determination

$$HCB = H / \{ 1.0 + \exp [ C_0 + C_1 * H + C_2 (H/DBH) + C_3 (H/DBH)^2 ] \}$$

$C_0, C_1, C_2$  and  $C_3$  are coefficients that vary with tree species (Table 2).

$$HCB = 141 / \{ 1.0 + \exp [ 3.764343 - 0.012033 * 141 - 0.529574 (141/28) + 0.017875 (141/28)^2 ] \}$$

$$HCB = 75.63 \text{ ft.}$$

$$\text{Let: } CR = \frac{H-HCB}{H}$$

$$CR = \frac{141-75.63}{141}$$

$$CR = 0.464$$

$$\text{Let: } CV = a \text{ (DBH)}^b * H^c * CR$$

$$CV = 14.55286 (28)^{0.97645} * 141 * 0.464^{1.46273}$$

$$CV = 17276.30 \text{ ft}^3$$

$$\text{Let: } Ac = \frac{k*CV}{(H-HCB)} \left( \frac{H-h}{(H-HCB)} \right)^{k-1}$$

$$Ac = \frac{1.805*17276.30}{(141-75.63)} * \left( \frac{141-65.37}{141-75.63} \right)^{1.805-1}$$

$$Ac = 536.44 \text{ ft}^2$$

$$\text{Let: } Hc = (h/3) + HCB$$

$$Hc = (65.37/3) + 75.63$$

$$Hc = 97.42 \text{ ft.}$$

$$Hw = H*0.36$$

$$Hw = 50.76 \text{ ft.}$$

### Critical Wind Speed Calculation

Let:

$$A = -Wt \cdot Hw \cdot \cos\alpha \cdot \cos\beta \cdot \sin\beta$$

$$B = [(Wt \cdot Hw \cdot \cos\alpha \cdot \cos\beta \cdot \sin\beta)^2 - (\sin^2\alpha + \cos^2\alpha \cdot \cos^2\beta) (Wt^2 \cdot Hw^2 \cdot \sin^2\beta - MM^2)]^{1/2}$$

$$C = \frac{1}{2} \cdot \rho l / g \cdot Cd \cdot Ac \cdot Hc \cdot (\sin^2\alpha + \cos^2\alpha \cdot \cos^2\beta)$$

$$u = \sqrt{\frac{A \pm B}{C}}$$

### Minimum Critical Wind Speed Calculation

Considering  $\alpha=0^\circ$  and  $\beta=6.3^\circ$ ,  $MM = 738086$  lb-ft

$$A = -10089 \cdot 50.76 \cdot \cos 0^\circ \cdot \cos 6.3^\circ \cdot \sin 6.3^\circ$$

$$A = -55857.32$$

$$B = [(10089 \cdot 50.76 \cdot \cos 0^\circ \cdot \cos 6.3^\circ \cdot \sin 6.3^\circ)^2 - (\sin^2 0^\circ + \cos^2 0^\circ \cdot \cos^2 6.3^\circ) \cdot (10089^2 \cdot 50.76^2 \cdot \sin^2 6.3^\circ - (738086)^2)]^{1/2}$$

$$B = 733628.7$$

$$C = \frac{1}{2} \cdot 0.08 / 32.19 \cdot 0.5 \cdot 536.44 \cdot 97.42 \cdot (\sin^2 0^\circ + \cos^2 0^\circ \cdot \cos^2 6.3^\circ)$$

$$C = 32.08$$

then

$$u = \sqrt{\frac{-55857.32 \pm 733628.7}{32.08}}$$

$$u = 145.35 \text{ ft/sec} \cdot 0.68 = 98.8 \approx 99 \text{ mph}$$

### Maximum Critical Wind Speed Calculation

Considering  $\alpha=180^\circ$  and  $\beta=6.3^\circ$

$$A = -10089 \cdot 50.76 \cdot \cos 180^\circ \cdot \cos 6.3^\circ \cdot \sin 6.3^\circ$$

$$A = 55857.32$$

$$B = [(10089 \cdot 50.76 \cdot \cos 180^\circ \cdot \cos 6.3^\circ \cdot \sin 6.3^\circ)^2 - (\sin^2 180^\circ + \cos^2 180^\circ \cdot \cos^2 6.3^\circ) \cdot (10089^2 \cdot 50.76^2 \cdot \sin^2 6.3^\circ - (738086)^2)]^{1/2}$$

$$B = 733628.7$$

$$C = 1/2 \cdot 0.08 / 32.19 \cdot 0.5 \cdot 536.44 \cdot 97.42 \cdot (\sin^2 180^\circ + \cos^2 180^\circ \cdot \cos^2 6.3^\circ)$$

$$C = 32.08$$

then

$$u = \sqrt{\frac{A \pm B}{C}}$$

$$u = \sqrt{\frac{55857.32 \pm 733628.7}{32.08}}$$

$$u = 156.875 \text{ ft/sec} \cdot 0.68 = 106.68 \text{ mph} \approx 107 \text{ mph}$$

Therefore; the difference between maximum and minimum critical wind speed is 8 mph.

## Appendix I. Classification of Wind by Beaufort Scale

Beaufort Number	Wind Speed (mph)	Descriptor	Effect observed
0	0 - 1	Calm	Smoke rises vertically
1	2 - 3	Light air	Smoke drifts; vanes do not move.
2	4 - 7	Light breeze	Leaves rustle; vanes begin to move.
3	8 - 12	Gentle breeze	Leaves in constant motion; lights flags extended.
4	13 - 18	Moderate breeze	Dust, leaves raised; branches moves.
5	19 - 24	Fresh breeze	Small trees begin to sway.
6	25 - 31	Strong breeze	Large branches of trees in motion; whistling heard in wires.
7	32 - 38	Near gale	Whole tree in motion resistance felt in walking against wind.
8	39 - 46	Gale	Twigs and small branches break; progress generally impeded.
9	47 - 54	Strong gale	Slight structural damage occurs; slate blown from roofs.
10	55 - 63	Storm	Trees broken or uprooted; considerable structural damage occurs.
11	64 - 73	Violent Storm	Damage all over
12	74 and above	Hurricane	Large-scale damage, calamity.



Appendix J. Calculations for Tree Fall Direction.

By considering the following information:

Wind direction : from WSW  
 Wind force : 7490 lbs.  
 Tree weight : 10089 lbs.  
 Tree lean angle ( $\beta$ ) :  $6.3^\circ$

then,

$$\begin{aligned} \text{Moment due wind (Mw)} &= \text{Wind force} \cdot \text{Hc} \cdot \cos\beta \\ &= 7490 \text{ lb} \cdot 97.4 \text{ ft} \cdot \cos 6.3^\circ \\ &= 725120 \text{ lb-ft.} \end{aligned}$$

$$\begin{aligned} \text{Moment due tree lean (Ml)} &= \text{Wt} \cdot \text{Hw} \cdot \sin\beta \\ &= 10089 \text{ lb} \cdot 50.76 \text{ ft} \cdot \sin 6.3^\circ \\ &= 56197 \text{ lb-ft.} \end{aligned}$$

To calculate the component for both moments (Figure a), we use the following equations.

$$\begin{aligned} \text{Mx} &= \text{Mw} \cdot \cos\theta_1 + \text{Ml} \cdot \cos\theta_2 \\ &= -725120 \text{ lb-ft} \cdot \cos 67.5^\circ + 56197 \text{ lb-ft} \cdot \cos 28^\circ \\ &= -227872 \text{ lb-ft.} \end{aligned}$$

$$\begin{aligned}
 M_y &= M_w \sin \theta_1 + M_l \sin \theta_2 \\
 &= 725120 \text{ lb-ft} \sin 67.5^\circ + 56197 \text{ lb-ft} \sin 28^\circ \\
 &= 719543 \text{ lb-ft}
 \end{aligned}$$

where

$$\begin{aligned}
 \theta &= \text{ATN}(M_y/M_x) \\
 &= \text{ATN}(719543/-227872) \\
 &= 72^\circ \text{ (azimuth)}
 \end{aligned}$$

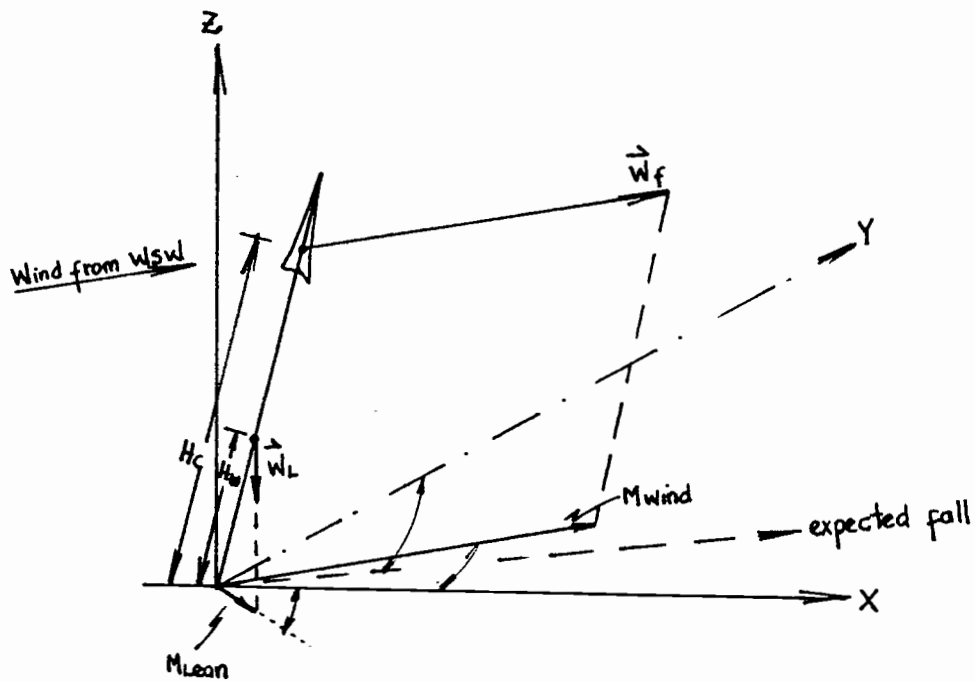


Figure a. Tree fall direction.

Appendix K. Computer Program to Calculate Critical Wind Speed.

```

10 ' Purpose: To Calculate the Critical Wind Speed
20 '
30 ' ----- VARIABLES -----
50 '
60 ' PL      = air density (lb/ft3)
70 ' CD      = drag coefficient
80 ' AG      = acceleration of gravity (ft/sec2)
90 ' k       = a species-specific parameter that
           = determines the shape of the profile
100 ' A,B,C   = regression coefficients for predicting
           = de total cubic foot crown volume
110 ' E,F,G,H = regression coefficients for predicting
           = height to live-crown base
120 ' HT      = height of the tree (feet)
130 ' DBH     = diameter breast height (inches)
140 ' WT      = tree weight (lb)
150 ' HC      = height to the center of force on the
           = crown (feet)
160 ' HW      = height to the center of gravity of the
           = tree (feet)
170 ' TL      = tree lean angle (degree)
180 ' LD      = horizontal distance of tree lean (feet)
190 ' MM      = maximum moment (lb-ft)
200 ' HCB     = height to live-crown base (feet)
210 ' CR      = crown ratio
220 ' CV      = total crown volume (feet3)
230 ' HA      = height from HCB to HT (feet)
240 ' AC      = projection area of the crown perpendicular
           = to the air flow (feet2)
250 ' DEN     = wood density (lb/ft3)
260 '
270 ' ----- ASSIGN CONSTANT -----
280 '
290 ' PL      = 0.08
300 ' CD      = 0.5
310 ' AG      = 32.19
320 ' Z       = PL/AG
330 ' DEN     = 49
340 ' K       = 1.80502
350 ' A       = 14.55286
360 ' B       = 0.97645
370 ' C       = 1.46273
380 ' E       = 3.764343
390 ' F       = 0.012033
400 ' G       = 0.529574
410 ' H       = 0.017875
420 ' ----- INPUT VARIABLES -----
430 '

```

```

440 INPUT "Enter height of the tree      (feet)      "; HT
450 INPUT "Enter diameter breast height (inches)    "; DBH
460 INPUT "Enter tree volume            (ft3)       "; VOL
470 INPUT "Enter tree lean angle        (degree)     "; TL
480 INPUT "Enter angle between wind     (degree)     "; WA
      direction and tree lean
490 '
500 WT = VOL*DEN
510 MM = -4270 + 73.58*WT
520 P  = TL*3.1416/180
530 Q  = WA*3.1416/180
540 R  = COS(Q)
550 S  = SIN(Q)
560 QA = COS(P)
570 QB = SIN(P)
580 HCB = HT / (1+EXP(E-F*(HT) -G*(HT/DBH) +H*(HT/DBH)2))
590 CR  = (HT-HCB)/HT
600 CV  = A*(DBH)B*HT*CRC
610 HA  = HT-HCB
620 AC  = ((K*CV)/(HT-HCB)) * ((HT-HA)/(HT-HCB))(K-1)
630 HC  = (HA/3)+HCB
640 HW  = HT*0.36
650 X   = -WT*HW*R*QA*QB
660 N   = 0.5*Z*CD*AC*(S2+R2*QA2)*HC
670 Y   = ((WT*HW*R*QA*QB)2 - (S2+R2*QA2)*(WT2*HW2*QB2-MM2))0.5
680 '
690 ----- WIND SPEED CALCULATION -----
700 '
710 PRINT "THE WIND SPEED IS = "; ((X+Y/N)0.5*0.68 " (mph) "
720 END

```

Appendix L. Record Data of Extreme Wind speed and Return  
Period for Corvallis, Eugene and Salem, Oregon.

Name	Period Record	Computed Return Period Wind (mph)				
		2 yr	10 yr	25 yr	50 yr	100 yr
Corvallis	1962-1973	45	53	57	60	64
Eugene	1943-1962	38	54	64	73	83
Salem	1943-1977	41	56	66	74	84
Average for Eugene and Salem		40	55	65	74	84

(from Wantz and Sinclair, 1981)