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A HANDBOOK ON THE USE OF TREES AS AN INDICATOR OF WIND POWER POTENTIAL

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Corvallis, Oregon

June 1979

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A HANDBOOK ON THE USE OF TREES AS AN INDICATOR OF WIND POWER POTENTIAL

FINAL REPORT

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EXECUTIVE SUMMARY

An important first step in the effective utilization of wind energy is the identification of locations with strong, persistent winds. This handbook describes techniques for selecting areas of good wind power potential using wind-deformed conifer trees. Wind-deformed trees were first used as yardsticks of wind power potential by P.C. Putnam in his survey prior to installation of the Smith-Putnam wind turbine at Grandpa's Knob. However, trees have been used for hundreds of years as an ecological indicator of wind direction, wind exposure and as a measure of the severity of wind and ice damage.

This handbook will describe techniques for "reading" the information written on the trees by wind. Techniques are described for determining the wind direction from trees and how this information can be used to infer possible wind-flow patterns. Seasonal variations in the wind have a pronounced effect on the type of wind deformation and these effects are characterized in this handbook.

Techniques for estimating the mean annual wind speed have been developed using three indices of wind effects on trees. These indices have been calibrated on two widely distributed species of conifers--Douglas-fir and Ponderosa Pine. The handbook describes the methods used to verify the calibration, the applications of the techniques developed and their limitations. One of the major limitations pointed out is that the indices are calibrated on only two species of conifer trees found in the western United States. The next edition of this handbook will extend these techniques to other types of trees found in other areas of the country. Another important consideration is that, while wind-flagged trees generally indicate strong winds, the absence of flagged trees should not be interpreted as indication of weak winds but rather as indication that the winds may be too variable in direction or that the diurnal variation in the wind is so great that wind flagging does not occur.

Trees also provide an indication of the occurrence of severe wind and ice loads. By examining external damage and internal

evidence of damage in the tree rings, the occurrence of severe wind or ice loads can be not only identified but also can be dated as to the year this damage occurred.

The main conclusions are that trees provide a simple, inexpensive and quick method for identifying promising locations where more detailed measurements can verify the wind power potential. For the small wind system user, flagged trees might be sufficiently quantitative evidence to justify installation of a wind energy conversion system. However, the lack of flagged trees should not disqualify a potential site but rather indicate the need for on-site wind measurements prior to wind system installation.

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INTRODUCTION

The first and crucial step in the effective utilization of wind power is the selection of a specific location for the wind energy conversion system (WECS). The magnitude of the wind resource available at a particular site will in large part determine the system's economic viability. High wind areas are conveniently located using a procedure known as "Biological Wind Prospecting."

This handbook describes such techniques for using trees as indicators of wind power potential and is aimed at providing the wind prospector with an initial assessment of the wind power potential. Such methods were first used in a wind survey by Putnam (1948) in Vermont prior to installation of the Smith-Putnam wind turbine at Grandpa's Knob. However, trees have been used for hundreds of years as rough ecological indicators of the direction, strength and severity of the wind.

Subsequent sections will describe these techniques for using trees in a wind survey, the role of vegetation indicators in site selection and the limitations of these techniques.

TREES AS INDICATORS OF PREVAILING WIND DIRECTION

In mountainous areas, winds are often complex and the available wind data are limited and provide little information on wind direction. One technique for determining the mean wind direction is tree flagging. A flagged tree is one in which the branches grow away from the prevailing wind direction, thus exhibiting a one-sided crown (see Figure 1). Holroyd (1970) mentions that phototropism (directed growth resulting from differential illumination) may cause branches to bend but the direction of the bending is usually random. Wind-flagged trees are distinguished from phototropic effects, because all branches in the same neighborhood point in a uniform direction.

Figure 1. A wind-flagged Douglas-fir.

Many studies have used tree deformation as an indicator of prevailing wind direction (Davies, 1814; Jefferson, 1904; Lawrence, 1939; Thomas, 1958; and Misawa, 1954). Among the most ambitious studies was Sekiguti (1951) who examined the direction of bending 230 persimmon trees in the Akaho Fan in Japan. A compass was used to measure the direction of bending. Standing 40-50 paces from the base of the tree, Sekiguti circled the tree until the direction of flagging was determined.

Holroyd (1970) examined 2,000 trees in New York's Whiteface Mountains. Flagging was noted on topographic maps (see Figure 2). Maps such as this one can show areas where the winds may converge, (indicating strong winds) or diverge (indicating weak winds); but most importantly, trees provide valuable information on prevailing wind direction. However, flagged trees only reflect the prevailing direction of the strongest winds, which may occur during only part of the year. *One should not assume that the wind that produced flagging at one location occurred at the same time as the wind that produced flagging at another location.* For example, in the Columbia River Gorge, strong easterly winter winds cause crowns to project to the west on the west end of the Gorge, and strong westerly spring and summer winds cause crowns to project easterly on the east end of the Gorge (Lawrence, 1939). If we assumed the prevailing winds occurred at the same time, then we would infer that the winds in the Gorge blow from center out in both directions which would be a very unusual situation.

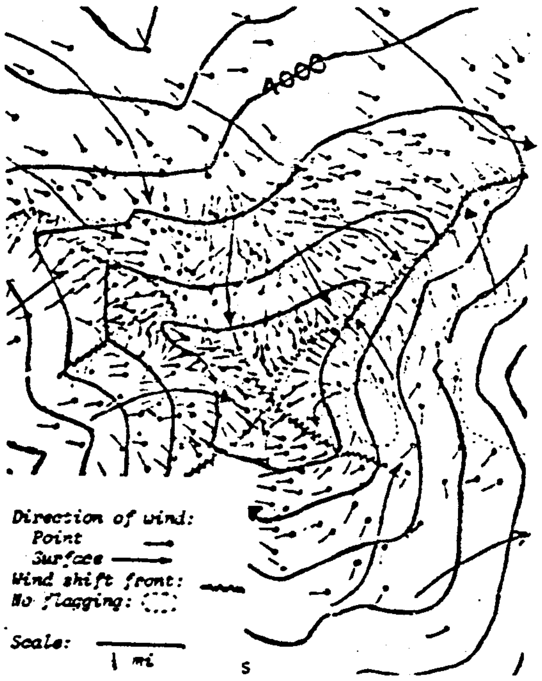

Figure 2. Wind direction in the Whiteface Mountains of New York inferred from flagged trees (Holroyd 1970).

To determine when wind flagging occurs, one needs to know characteristics of wind during different seasons on trees. Lawrence (1939) has provided some guidance on a method for determining the season during which flagging occurs.

WINTER WIND FLAGGING

Winter-flagged trees are characterized by a tattered appearance with the longest branches projecting downwind. The windward side may have no branches or may have only small recently formed twigs and branches, irregularly distributed about the stem. On the windward side, long branches will be absent and remaining branches will be much bushier. The branch ends on the windward side will appear as if they have been clipped by a gardener's shears (see Figure 3).

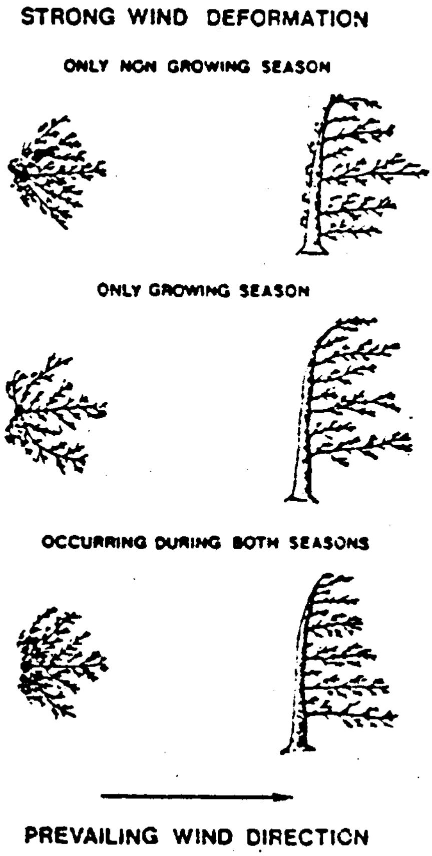

Figure 3. Flagging characteristic of wind from different seasons.

Winter flagging may be caused by ice and breakage from severe winds, desiccation caused by strong dry winter winds, and wind sway which disrupts roots on the windward side and results in greater growth the following spring on the leeward side of the tree.

GROWING SEASON WIND FLAGGING

Trees exposed to strong winds during the growing season have branches that appear to have been entrained in the prevailing winds. Trunks are often bowed slightly leeward. Well developed branches arise on all sides of the tree but those emerging from the side facing the prevailing winds have been swept around toward the leeward side (see Figure 3).

FLAGGING BY WINDS DURING BOTH THE GROWING SEASON AND WINTER SEASON

If both winter and growing-season winds come from the same direction, the trees commonly exhibit a smooth appearance on the windward side (see Figure 3). Trees subjected to winds of opposite direction during the winter and the growing season will exhibit both effects, and long branches will be found only in the directions perpendicular to the prevailing wind directions. Where the winds during the nongrowing season are at right angles to the growing-season winds, the branches often have a dense-shape on the side opposite the growing-season winds. These possible shapes are shown in Figure 4.

It has been shown that wind will affect the tree throughout the year. By careful examination of the tree one can determine if there are seasonal differences in the prevailing direction. It should be recognized since most winter damage is mechanical (breakage of branches and abrasion of leaf or needle surfaces); these effects may be the results of either persistent strong winds or isolated severe winds.

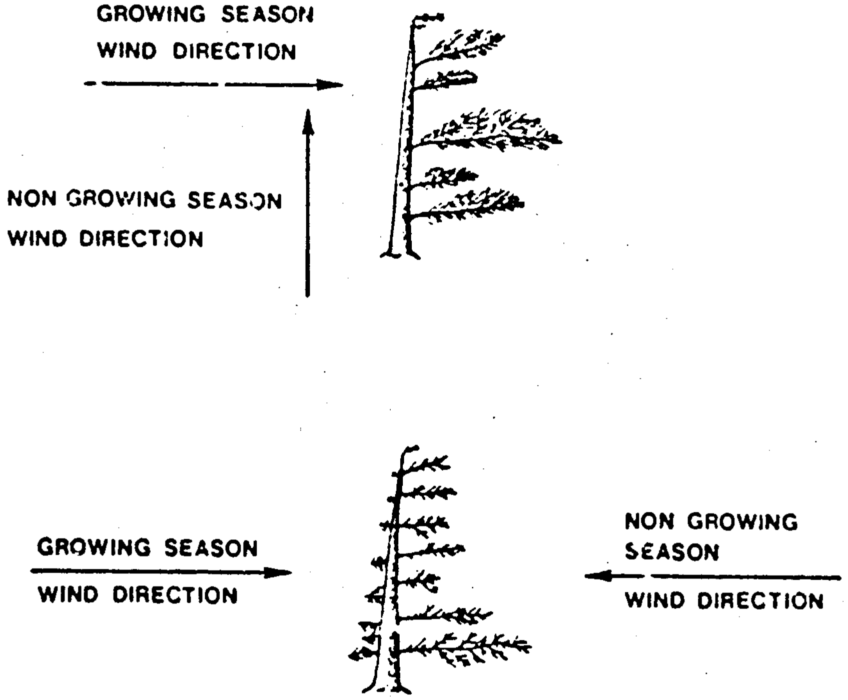

Figure 4. Characteristic wind deformation when the wind comes from a different direction during the nongrowing season.

TREES AS INDICATORS OF MEAN WIND SPEED

Trees, as Putnam (1948) pointed out, should be excellent indicators of wind power potential. Light winds (below 4 m/s) have little effect on trees. Similarly, wind turbines rarely operate below 4 m/s. Occasional severe winds may temporarily damage a tree but usually they have little permanent effect on its shape. The same may be true for wind turbines that often do not operate in winds greater than 25 m/s and may even be damaged by severe winds. Different wind turbines often have different wind speeds at which they begin to produce power; the same seems to be true of different species of trees. Different trees have different thresholds at which they begin to display wind deformation.

Putnam (1948) observed that tree deformation appeared to be a function of the mean annual wind speed. This observation appears to be consistent with the findings of Hewson et al., (1977). In Hewson's studies, three indices of tree deformation were calibrated against a number of wind characteristics including mean annual wind speed, mean growing-season wind speed, mean nongrowing-season wind speed and percentage of winds from the prevailing direction. The results indicated the mean annual wind speed was the wind characteristic that best correlated with the indices of tree deformation. These indices of tree deformation by wind were developed primarily for coniferous trees and were calibrated on the two predominant species of coniferous trees in the western United States--Douglas-fir *(Pseudotsuga menziesii)* and Ponderosa Pine *(Pinus ponderosa)*.

Indices of wind deformation have been developed for other forms of trees such as hemispherical crowned trees by Barsch and Weischet (1963) and for pyramid, columnar and hemispherical crowned trees by Yoshino (1973). Calibration of these forms will be reported later.

Douglas-fir and Ponderosa Pine were chosen for use in the calibration of indices because they are widely distributed both with elevation and in geographical area (see Figure 5). Both species appear to

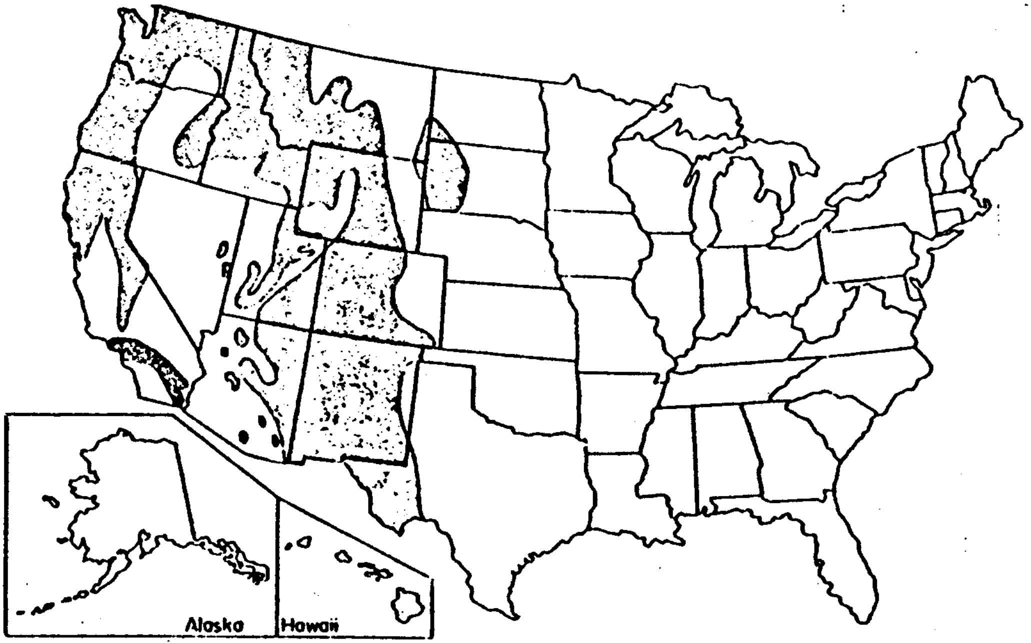

Figure 5. The geographical distribution of Douglas-fir and Ponderosa Pine.

have similar response to wind. The same can not be said for other species of conifers. Trees of the genus *Abies* (firs) do not show any evidence of wind deformation below 6 m/s. The genus *Larix* (Larch) appear to be more sensitive to winds than Douglas-fir and Ponderosa Pine. Even different species within a genus may react differently. High altitude pines such as Whitebark Pine *(Pinus albicaulis)* and Bristlecone Pine *(Pinus aristata)* appear to be somewhat less sensitive to wind than Ponderosa Pine.

DESCRIPTION OF THE INDICES OF WIND EFFECTS ON TREES

The first index of wind effects on trees is the *Griggs-Putnam Index*. The index is based on the pioneering work of R.F. Griggs, a botanist who collaborated with P.C. Putnam in the survey of wind power potential in New England prior to the installation of the Smith-Putnam wind turbine on Grandpa's Knob in Vermont. This index, (see Figure 6),

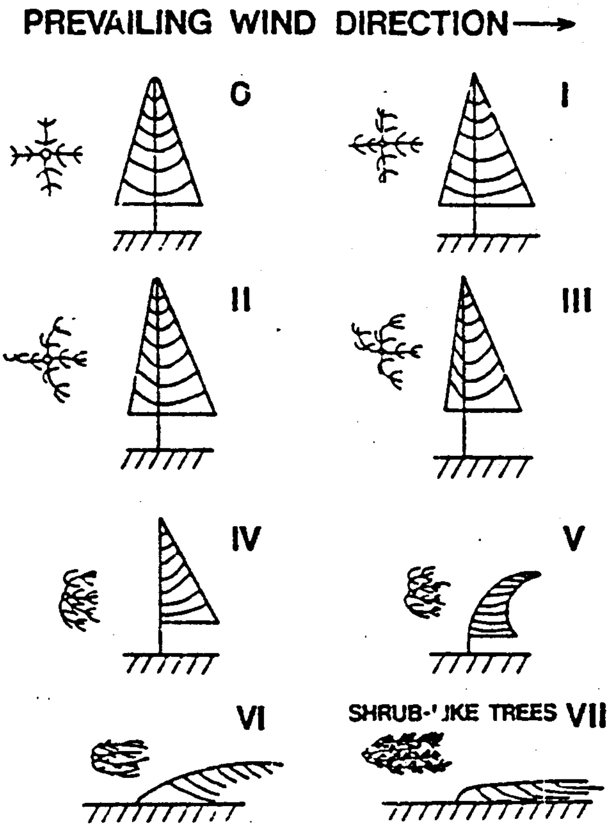

Figure 6. The Griggs-Putnam Index of deformation.

is a subjective scale based on the degree of the tree's response to the wind.

The degree of response has been divided into the following seven classes:

Class 0 indicates *no effect*. Careful examination of needles, twigs and branches indicates that the wind had no noticeable influence on the tree.

Class I is *brushing*. The small branches and needles appear bent away from the prevailing wind direction. The tree crown may appear slightly asymmetric upon careful examination.

Class II indicates *light flagging*. The small branches and the ends of the larger branches are bent by the wind giving the tree a noticeably asymmetric crown.

Class III indicates *moderate flagging*. The large branches are bent toward the leeward side of the tree giving the tree a nearly one-sided crown.

Class IV is *strong flagging*. All branches are swept to the leeward and the trunk is bare on the windward side. The tree resembles a banner.

Class V is *partial throwing*.* A partially thrown tree is one in which the trunk as well as the branches are bent to the lee. The trunk may be bent concave or convex, but it rises vertically near the ground with the degree of bending increasing near the top of the trunk.

Class VI is *complete throwing*. The tree grows nearly parallel to the ground and along the path of the prevailing wind. The larger branches on the leeward side may extend beyond the tip of the trunk.

Class VII indicates *carpeting*. The wind is so strong or accompanying conditions so severe (i.e., ice particles) that the tree takes the form of a shrub. Upright leaders are killed, lateral growth predominates and the crown grows across the ground like a prostrate shrub.

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*Throwing should not be confused with the type of throwing caused by root break or soil failure. Throwing as defined here can be differentiated from that caused by root break or soil failure by examining the angle of the trunk with ground surface. Root break or soil failure causes trees to tilt, projecting the trunk from the ground at an angle. Throwing caused by strong persistent winds results in the trunk rising perpendicular from the ground and then bending above the ground.

A second index, similar to the Griggs-Putnam Index, is the *Deformation Ratio.* The deformation ratio represents the amount of crown asymmetry and trunk deflection caused by the wind. The technique involves measuring the angles formed by the crown and stem on the windward and leeward side of a tree from photographs taken perpendicular to the direction of maximum asymmetry. The deformation ratio is given by D, where:

$$D = \frac{\alpha}{\beta} + \frac{\gamma}{45^\circ} \qquad \left[1 \leq \frac{\alpha}{\beta} \leq 5\right]$$

The angle α is the angle formed by crown and trunk on leeward side; β is the angle formed by the crown and the trunk on the windward side; and γ is the degree of stem deflection (see Figure 7).

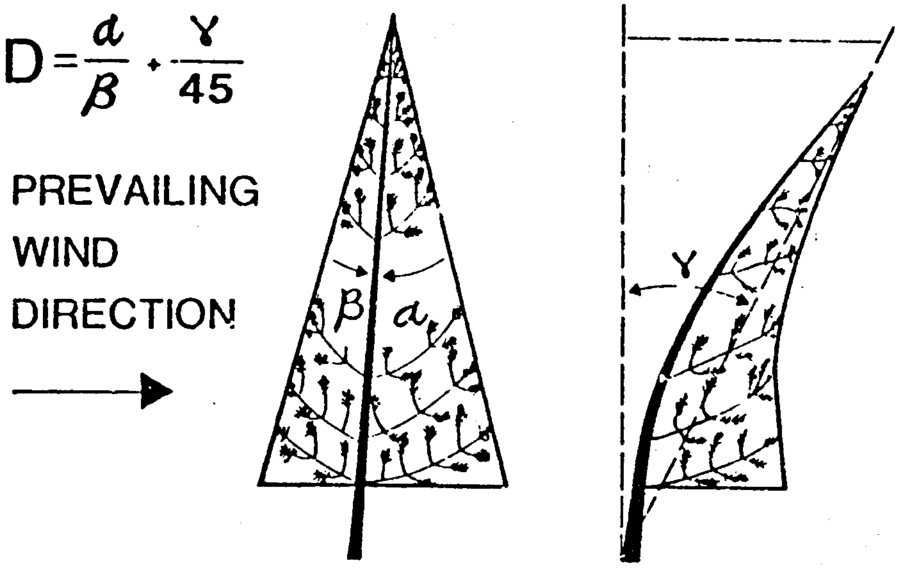

Figure 7. The technique for determining the Deformation Ratio.

A third index of tree deformation by the wind is the *Compression Ratio* which measures the wind's influence on the formation of reaction wood. Reaction wood is "abnormal" wood laid down on a particular side of the tree when the tree is displaced from the vertical by some force such as wind. In trees exposed to prevailing winds, reaction wood is found on the leeward side of conifers and the windward side of deciduous trees. Reaction wood is called compression wood in conifers and tension wood in deciduous trees. Figure 8 illustrates an eccentric radial growth pattern of a tree growing in a windy location.

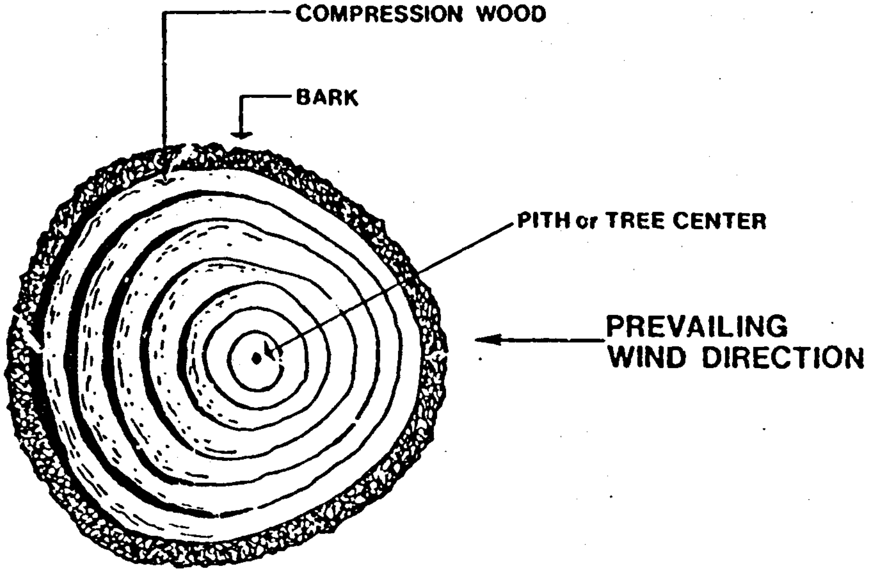

Figure 8. A typical cross section of a conifer tree growing in a windy location.

The compression ratio may be determined either by looking at a radial cross section of the tree or by taking an increment core from the windward and leeward side of the tree. Tree cores and radial cross sections are first cross-dated as in Figure 9. The growth increments for each year are then measured in the leeward and windward directions. The compression ratio for conifers is the ratio of leeward growth to windward growth. The compression ratio should be calculated over the last five years, because that period would be the most representative of the tree's most recent exposure to the wind.

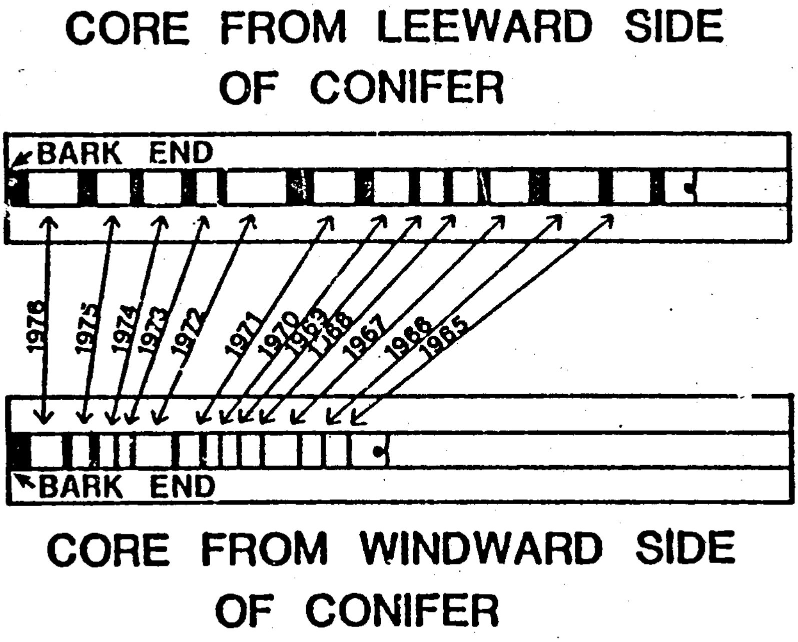

Figure 9. Mounting and cross-dating core samples from the windward and leeward sides of the tree.

Young trees may be sheltered from the wind by taller trees, so trees that are tall enough to be growing at a height swept by the turbine should be used as indicators of wind power potential. Trees are seldom taller than 30 meters in windy locations, which provides an upper limit for the size tree that can be sampled. A good lower limit is 10 meters although this is not always possible, particularly in windy or high elevation locations.

SAMPLING TECHNIQUES

Using trees to indicate wind velocity is subject to a number of practical limitations which have a bearing on the method of selecting indicator trees. Of greatest concern is the tree's exposure to the wind. Trees selected as indicators must be well exposed to the prevailing winds. Seldom do trees in a forest stand extend far enough above the canopy to be in an air stream undisturbed by the other trees. Isolated trees or those in small widely spaced groups should be favored as wind velocity indicators. Several well exposed trees should be selected and the average index value for the trees should be used to characterize the site.

All trees should be as close to the same height as possible, if they are going to be used to compare the wind-energy potential of several locations. Wind speed increases dramatically with height up to 10 meters. Above 10 meters this change in wind speed, although significant, is less pronounced. To decrease the effect of vertical wind speed variations, trees selected should be 10 meters or taller. This restriction does not apply at high wind locations where trees are restricted in height due to strength of the wind. Also, trees should be of the same species if they are being used to rate potential sites. Douglas-fir and Ponderosa Pine react very similarly to the mean annual winds above 5 m/s. Below that speed, Douglas-fir are somewhat more sensitive to wind than the Ponderosa Pine.

Salt damage in coastal areas may enhance the degree of deformation. Coastal trees deformed by wind may be compared to one another, but they should not be compared to wind-deformed trees in noncoastal locations.

Other nonwind factors may cause a characteristic one-sided crown. The growth of two trees side by side, for example, will result in both trees having an asymmetric crown. If one tree is removed, the other will look wind-flagged. Always look for evidence of past competition. Soil or snow creep, an occasional severe ice storm, pruning or logging damage may all result in an asymmetric crown form not associated with wind.

Factors other than wind can affect the amount of compression wood. Younger trees or fast-growing trees will put on more compression wood than older or slower-growing trees. Coniferous trees growing on slopes put extra wood on the uphill side of the stem or on the downhill side when soil or snow creep is occurring. Trees that have been tilted also put on compression wood in response to displacement from the vertical. The character of the crown strongly affects the amount of compression wood. Trees with deep crowns are less affected than those with crowns only in the upper portion of the tree. The number and weight of branches on each side of the tree will also affect the amount of compression wood that is formed.

MEAN WIND SPEED AND TREE DEFORMATION

This section describes the statistical relationships that have been developed between the indices described and the mean annual wind speed. The results described here are based on a three-year study in which over 60 study sites were set up and nearly 20 species of trees examined. However, the only sites used in the calibration of indices were those sites with Douglas-fir or Ponderosa Pine and having at least one year of wind data. Locations along the coast were not used because of the possibility of salt spray enhancing wind deformation. Figures 10, 11 and 12 show the relationships between the mean annual wind speed and the three indices.

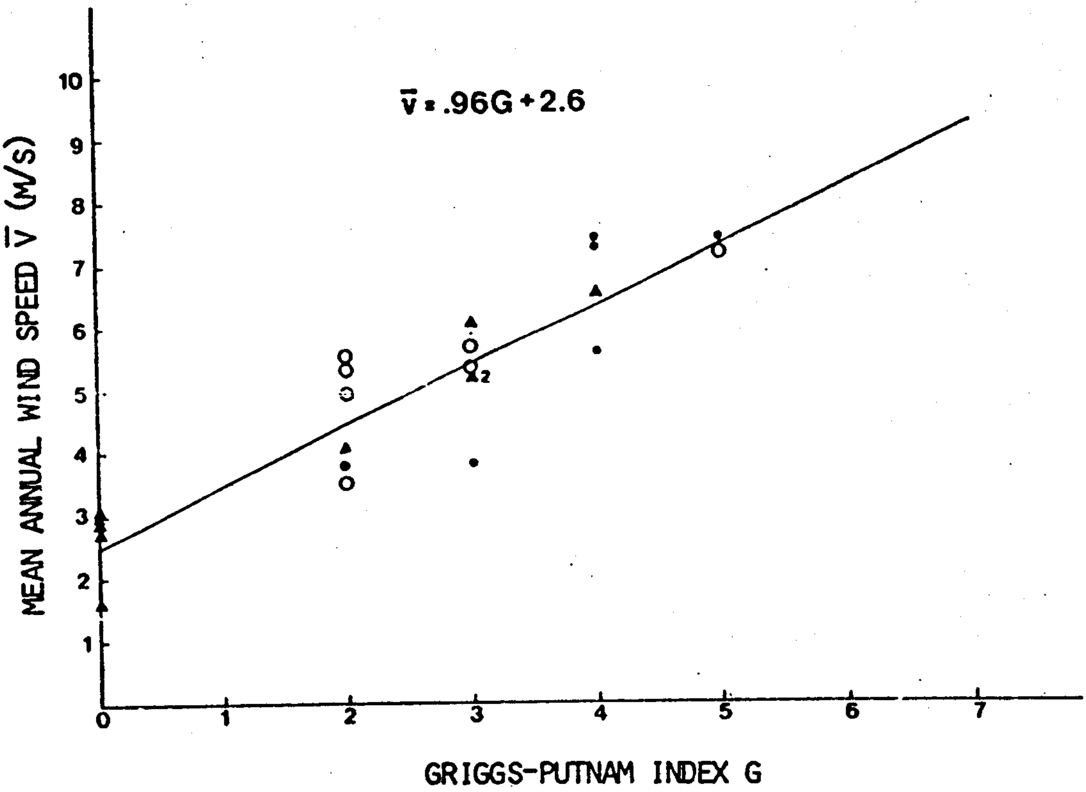

Figure 10. The relationship between the Griggs-Putnam Index and mean annual wind speed. Open circles represent locations where contact anemometer data were used. Closed circles represent locations with less than four years of data, and triangles denote more than four years of wind data.

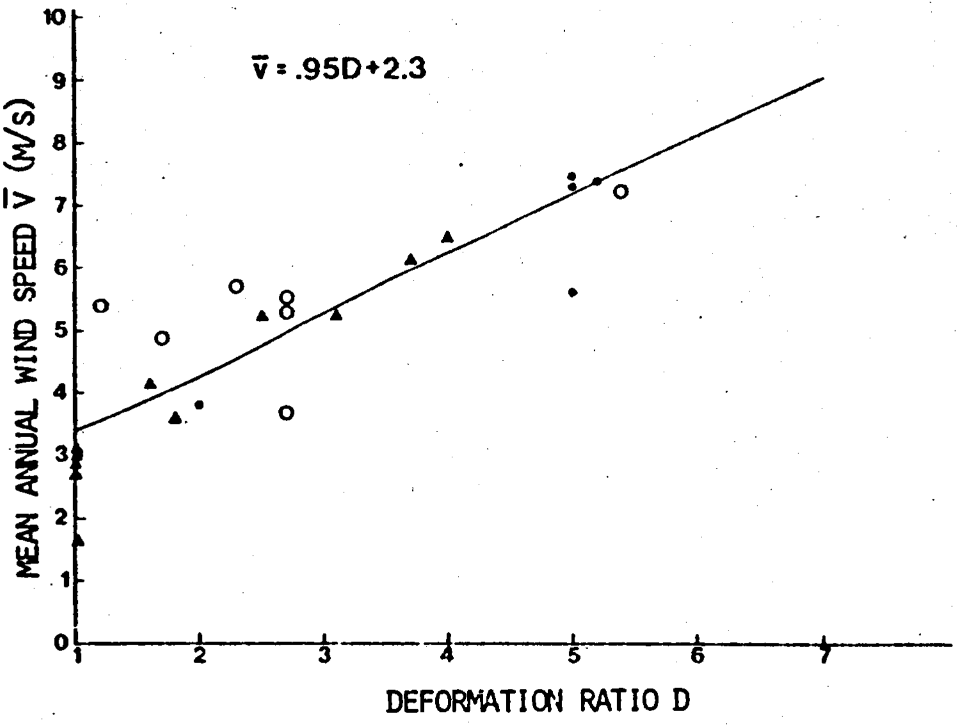

Figure 11. The relationship between the Deformation Ratio and mean annual wind speed.

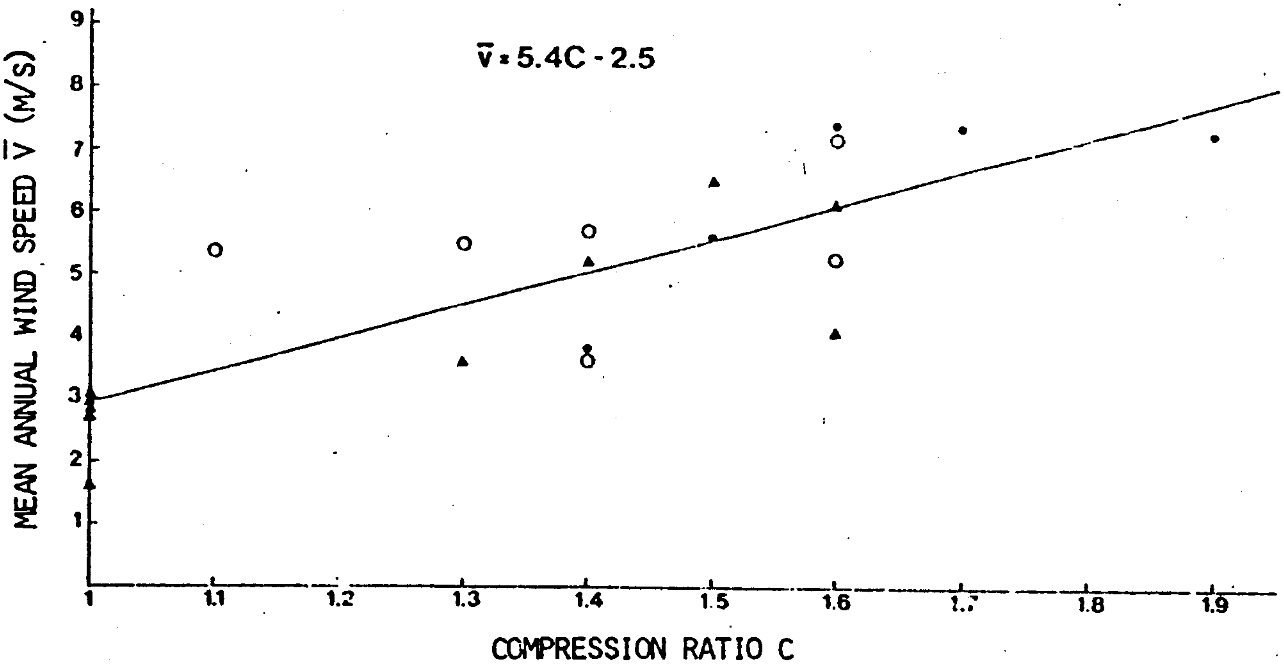

Figure 12. The relationship between the Compression Ratio and mean annual wind speed.

Indices are validated by predicting mean annual wind speed for locations not included in the calibration of the indices. This was done by using a "Jackknife" statistical technique (Quenouille, 1956 and Gray and Schucany, 1972), and involved dividing the sample into as many subsets as there are data points. Linear regression was performed for each subset, alternately leaving out one of the coordinates. Thus, for each regression relation, an error estimate is obtained for the coordinates not included. In this way the mean predictive error for each coordinate is based on regression equation that was developed on a subset that did not include that coordinate. The mean error for each of the indices is shown in Table 1.

Table 1. The mean prediction errors for the three indices of wind effects on trees.

Index	Prediction Error (%)
Griggs-Putnam Index	15
Deformation Ratio	18
Compression Ratio	20
Average Error	18

The best estimate of mean annual wind speed is obtained using the Griggs-Putnam Index. This relationship is displayed in Figure 13. The Deformation Ratio provides a backup index or can be used when only photographs are available in lieu of direct examination. The Compression Ratio is a useful tool for examining the history of wind effects on trees and can be used by examining the tree rings from stumps when all trees have been cut down.

USING TREES AS INDICATORS OF MEAN WIND SPEED

These indices of wind speed should be used only as rough estimates of mean annual wind speed. They have been calibrated at only 23 locations and many of these locations have only a year or two of wind data. According to Corotis (1977) the error in determining mean annual wind speed with only a year of data may be ±10%.

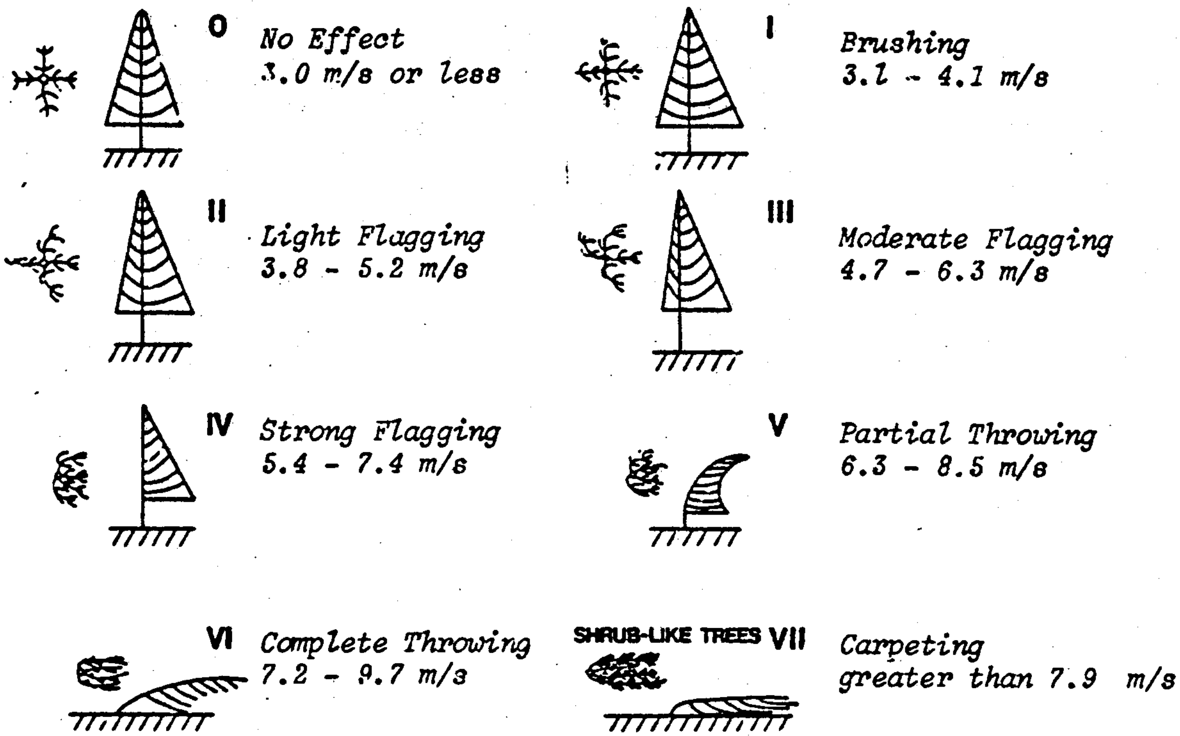

Figure 13. Wind deformation and the wind velocity that may produce that deformation.

Additional error in the mean speed may be due to the use of wind-run contact anemometers at seven of the locations used in the calibration of the trees. The error introduced by using contact anemometers for measuring mean annual wind speed may approach ±11%.

Error can also be introduced in the process of estimating the degree of flagging. Overestimating or underestimating the Griggs-Putnam Index value, for example, may result in 20 to 40% additional error in the estimate of mean annual wind speed. This error can be reduced by having several people estimate the index values, using more than one tree and using all three indices.

Although wind-flagged trees indicate strong winds, a lack of flagging does not necessarily indicate that the wind is not strong. Situations may occur where strong winds come from three or more directions, but their persistence is insufficient from any of the directions to cause noticeable deformation. Also at locations where afternoon winds may be strong but decrease considerably at night, trees are unlikely to be wind deformed.

Preliminary investigations indicate that relationships developed between the indices and mean annual wind speed, although valid only for Douglas-fir and Ponderosa Pine appear to work reasonably well on other species of pine and hemlocks. One should assume that the uncertainty in the estimates of mean wind speed will be much greater when applied to species other than Douglas-fir and Ponderosa Pine. The relationships are not valid at all for true firs *(Abies)* or any deciduous tree (like oaks, aspen or fruit trees).

TREES AS INDICATORS OF SEVERE WIND OR ICE DAMAGE

Severe wind and ice may present problems for wind turbines, their support structures, and power transmission lines from the turbine. Therefore, wind turbines should be placed away from such occurrences. Trees may be used as such indicators because they record evidence of these destructive forces in their outward appearance and in the wood tissue of their trunks.

Pillow (1931) found a change in the tree ring structure of pine trees in Florida that had been exposed to the 1926 hurricane. In each tree the most recent ring on the windward side was much narrower the following spring. Rings on the leeside were much wider, but by 1928 this asymmetric growth had disappeared. This narrow streak of abnormal ring structure was suggested to be the result of a temporary bending of the tree by the severe wind. Abnormal ring structure can thus be used to identify the occurrence of occasionally severe winds.

The external appearance of trees also provides clues of severe wind damage. Broken branches, wind throw (leaning trees) and blow-down all provide evidence of severe winds. Curtis (1941) estimated that the time required for a hurricane to demolish a whole forest is perhaps 150 years. Storms with a shorter return period may damage individual trees or pockets of trees but are unlikely to influence a whole forest. Wald (1934) used trees and other plants to map locations of possible heavy ice loads.

Patterns of suppressed tree rings (narrow rings) followed by released tree rings (wide rings) may be used to interpret which trees had been subjected to defoliation by severe wind or ice loading. However, patterns of narrow and wide rings may result from reduced growth due to crowding or shading by nearby trees and their subsequent release growth due to removal of competitor trees. Insect or fire damage could also produce an alternating pattern of narrow and wide rings.

Both external and internal evidence should be examined when using trees as an indicator of severe wind and ice damage. The external evidence may include:

- fallen trees,
- leaning trees,
- trees with broken branches or tops,
- dead branches on the ground, and
- trunks that have gnarled knots where branch stubs have healed imperfectly.

Internal evidence of severe wind or ice damage can be found by examining the tree ring patterns looking for suppressed and released ring patterns, or temporary patterns of eccentric growth. Ring patterns can then be used to estimate the date of occurrence of the wind or ice damage.

CONCLUSION

The results described in this handbook indicate that trees can be used successfully to determine mean wind direction, identify the occurrence of severe wind or ice loads and most importantly, can be used to estimate mean annual wind speed. While these estimates of mean annual wind speed are subject to some uncertainty, they nevertheless provide a simple, inexpensive and quick method for identifying promising locations where more detailed measurements can verify the wind power potential. For the potential small wind system user, flagged trees might be sufficiently quantitative evidence to justify installation of a wind turbine. However, the lack of flagged trees should not necessarily disqualify a potential site, but rather should suggest the need for on-site wind measurements prior to wind system installation.

These techniques have been tested and validated for only two species of trees found in the Pacific Northwest--Douglas-fir and Ponderosa Pine. The next edition of this handbook will extend these techniques to other generic classes of trees and describe techniques for identifying wind-deformed trees from aerial photographs.

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TREES AS AN INDICATOR OF WIND POWER POTENTIAL

by

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INTRODUCTION

A necessary condition for utilizing wind energy is a knowledge of the strength and persistence of wind. This is particularly true here in the Pacific Northwest where in mountainous terrain the wind may vary considerably over distances less than a kilometer. Since power is proportional to the cube of the wind speed, it is crucial to know the strength of winds at sites being considered.

One of the first steps in determining the feasibility of utilizing wind as a source of energy should be a wind power survey, the purpose of which is to discover windy locations for wind power plant installation. This paper will describe a wind survey technique being developed by Oregon State University under a Department of Energy contract. The technique, called "Biological Wind Prospecting", uses plants as indicators of the strength of the wind. Plants provide a quick, at a glance, indication of strong winds and when calibrated by the degree of wind shaping provide a rough, first-cut assessment of wind power potential.

DEVELOPMENT OF THE TECHNIQUE

Putnam (1948) was the first to use vegetation as a tool in wind power surveys. He classified trees by various degrees of wind deformation which included:

(a) *Brushing*: the branches are bent to leeward only slightly, like the hair in a pelt which has been brushed one way.

(b) *Flagging*: the branches stretch out to the leeward and the trunk is bare on the windward side.

(c) *Wind clipping*: the leading shoots are suppressed and held to an abnormally low level. The upper surface is as smooth as a well kept hedge.

(d) *Tree carpets*: the tree is prostrate and spreading over the ground.

(e) *Winter killing and resurgence*: the leading shoots are killed during the winter.

(f) *Ice deformation*: the formation of ice on the branches in winter causes breakage, leading to a much branched "candelabrum" tree.

Putnam assumed that tree deformation was a function of the annual mean wind speed. He noted that some components of the annual mean wind speed may not contribute to tree deformation; for example, light winds will have little effect on tree form and occasional severe winds without breakage do not affect tree shape but contribute to the annual mean velocity. However wind turbines, he reasoned, react similarly using only speeds in a certain range. In addition, he found turbine output could be predicted from the annual mean wind speed because speed frequency distribution curves in New England are of the same statistical type. Therefore tree deformation should also be a function of the annual mean wind speed.

Putnam's technique, although based on fragmentary observations of trees and often only estimated wind data, showed good agreement between the degree of tree deformation and annual mean wind speed. Barsch and Weischet (1963) and Yoshino (1973) also found agreement between measured wind speeds and the degree deformation of trees. However, none of the above studies attempted to develop relationships between wind velocity and tree form.

In July 1976, Oregon State University initiated a similar study whose purpose was to calibrate in terms of wind characteristics various indices of wind effects on vegetation. These indices, when calibrated, could in turn be used as a first step in selecting sites for wind energy conversion systems.

The first year of the study began with the establishment of a library of information on the affects of wind on vegetation. In addition, five indices of wind affects on coniferous trees were developed and the calibration process was commenced. The results of the first year's research are described by Hewson et al. (1977) and Hewson and Wade (1977).

During the second year, the study of the relationship between the index values and wind characteristics was expanded to over 40 locations in Washington, Oregon, Nevada and California. The primary emphasis in this phase of the study was the calibration of two widely distributed species of conifers, Douglas-fir (Pseudotsuga menziesii) and Ponderosa Pine (Pinus ponderosa) in terms of annual mean wind speed.

Preliminary calibrations have been made on three indices:

Griggs-Putnam Index: a subjective rating scale similar to that developed by Griggs and used by Putnam (1948). The original index has been described earlier.

Deformation Ratio: an indicator of the degree of wind induced crown asymmetry and trunk deflection. The ratio is computed by measuring the angle formed by the crown and the trunk on the leeward side of the tree and dividing by the measured angle formed by the crown and the trunk on the windward side of the tree. The sum of this ratio and the quantity $\gamma/45$, where γ is the angle of permanent deflection of the tree trunk from the vertical, is defined as the deformation ratio, as illustrated in Figure 2.

Compression Ratio: a measure of the influence of wind on the formation of reaction wood and the resulting eccentric radial growth. The ratio is calculated by measuring the increment of growth on the lee side of the tree over some period of time during which winds have been measured and dividing by the increment of growth over the same period on the windward side of the tree (see Figure 3).

Two other indices have been examined but not calibrated. They are:

Shape Index: a measure of the relative influence of wind on apical (height) and radial growth. The index is computed by dividing the circumference of a tree at 1.5 m by its height.

Eccentricity: an indicator of the departure from circularity of the trunk of the tree. This index is computed by measuring the major and minor axes of the tree at 1.5 m and computing eccentricity.

These five indices are calculated from data collected in the field. At each experimental site wind data are being gathered so that the relationship between the wind and each index value can be determined. At many of the locations winds are being measured using recording anemometers and wind vanes, from which monthly averaged wind speeds and directions can be determined. The sites that have been chosen for study have been selected either because of the presence of wind deformed vegetation or because wind information and trees happen to be available in the same area. Wherever possible these shorter period wind measurements are being correlated with nearby longer period records to determine how representative the short period records are.

The procedure needed to develop index values for each tree involves first of all a physical examination of the tree and its environment which includes amount and direction of wind induced flagging, nearby sheltering vegetation which may affect tree form, and terrain influences that may affect stem shape. Measurements are made of tree trunk height and circumference for the Shape Index, major and minor axes of the trunk for the Eccentricity, and the altitude of the location where the tree is growing. A photograph is taken from a point perpendicular to the direction in which the tree is flagged for later laboratory analysis of the degree of wind flagging for determining the Griggs-Putnam Rating and the Deformation Ratio. For the Compression Ratio the tree is cored on the side facing the prevailing wind direction at breast height, 1.5 m, and also on the opposite side of the tree trunk. The two holes in the tree are plugged and the cores are mounted in blocks and labeled for laboratory analysis.

The final step in the field analysis may include the collection of needles, bark and a cone so that positive species identification can be made if necessary by a dendrologist. Up to the present time the study has concentrated on Douglas-fir and Ponderosa Pine, but eight other species of conifers have also been included.

The wind data are processed at Oregon State University to determine hourly, monthly and annual mean wind speed and the percent frequency of winds from each direction. Field data on each tree are processed and the indices defined earlier are calculated. Tree cores are sanded, polished, cross dated and measured for growth increment. The data on the tree rings are cross dated, as shown in Figure 4, to insure that the rings on each side of the tree are aligned and represent the year assigned.

RESULTS

Index values have been computed at 24 locations which have a year or more of wind data. Relationships between the indices G (Griggs-Putnam Index), D (Deformation Ratio), C (Compression Ratio) and $\overline{V}$ (the annual mean wind speed) are given in Table 1 along with r, the correlation coefficient, ME the mean error in the prediction of mean wind speed and P_{25} the percent of time the prediction error is likely to exceed ± 25%.

Table 1. Relationships between $\overline{V}$ and index values.

Index	Relationship	r	ME (%)	P_{25} (%)
G	$\overline{V} = 1.05G + 2.72$	.90	14	8
D	$\overline{V} = 0.9D + 3.00$	.88	15	21
C	$\overline{V} = 3.6C + 0.32$	.67	22	32

Mean predictive errors were calculated using a Jackknife statistical technique (see Quenouille, 1956 and Gray and Schucany, 1972). The technique involves dividing the sample into as many subsets as there are data points. Regression relations are calculated for each subset leaving out one of the data points. For each regression relation an error estimate is obtained for the point not included. In this way the mean predictive error for each data point is based on a regression equation which does not include that point. The mean error for all the data points is the mean error expected when using a regression relationship developed with all of the data points. In Table 2 and Figures 5 and 6 relationships are shown between the annual mean wind speed and the three indices.

Table 2. Relationship between the Griggs-Putnam Index (G) and the annual mean wind speed ($\overline{V}$) in m sec^{-1}.

G	$\overline{V}$
0	< 3.3
1	3.3 - 4.2
2	4.3 - 5.1
3	5.2 - 6.2
4	6.3 - 7.5
5	7.6 - 8.5
6	8.6 - 11.0*
7	> 11.0*

* Estimated since data are not available for these speed ranges.

Relationships have also been developed between the percent of useable winds P and the indices (see Table 3). The percent of useable winds is defined as the percent of time the winds occur in the range

Table 1. Relationships between $\overline{V}$ and index values.

Index	Relationship	r	ME (%)	P_{25} (%)
G	$\overline{V} = 1.05G + 2.72$	.90	14	8
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C	$\overline{V} = 3.6C + 0.32$	.67	22	32

3.6 - 22.3 m sec^{-1} which is the speed range at which many commercial wind turbines operate.

Table 3. The relationship between P (percent of useable winds) and $\overline{V}$ (the annual mean wind velocity) in m sec^{-1} (other parameters are the same as in Table 1).

Index	Relationship	r	ME (%)	P_{25} (%)
G	P = 12G + 29	.90	15	8
D	P = 10D + 33	.84	19	21
C	P = 18C + 32	.60	32	41

The C index obviously has the greatest amount of error because asymmetric growth may be the result of a number of other factors not related to wind. However, if a large number of trees (six or more) are sampled at each location this error should decrease.

We have also found that coniferous trees in windy locations are shorter, have a greater circumference, trunks are generally egg shaped in a radial cross section with the narrow end pointed in the direction of the prevailing wind, and the direction of the crown and trunk asymmetry are strongly correlated with the prevailing wind direction.

During the next year research will focus on extending these techniques to both other coniferous and deciduous trees. Work is also proceeding in developing techniques for identifying wind deformed vegetation from aerial photographs. The use of aerial photographs would speed the process of selecting sites with good wind power potential.

CONCLUSIONS

Tree deformation appears to be a sensitive indicator of annual mean wind speed and direction and trees may be used to estimate both the annual mean wind speed (mean error ± 17%) and percent of useable winds (mean error ± 22%). This technique could appropriately be used as a first stage in a wind survey prior to instrumentation with anemometers.

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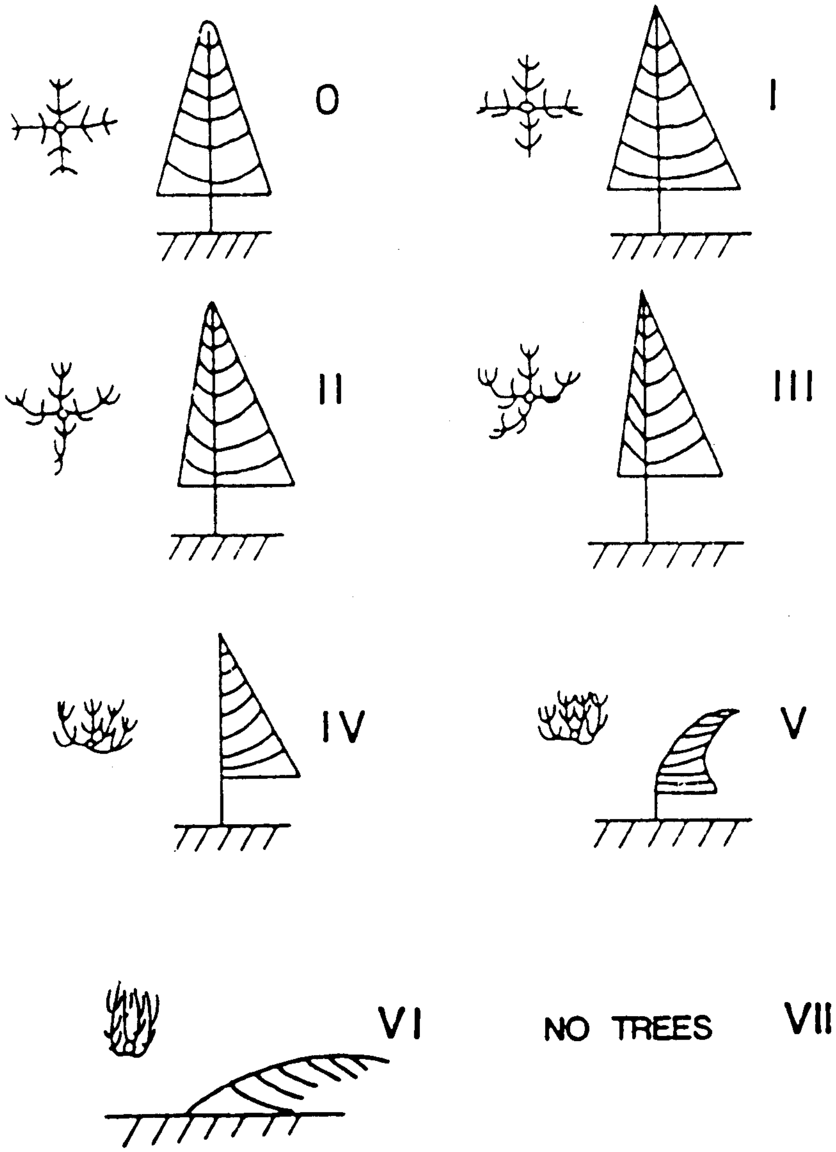


Figure 1. A representation of the Griggs-Putnam Index which is based on external wind deformation of coniferous trees.

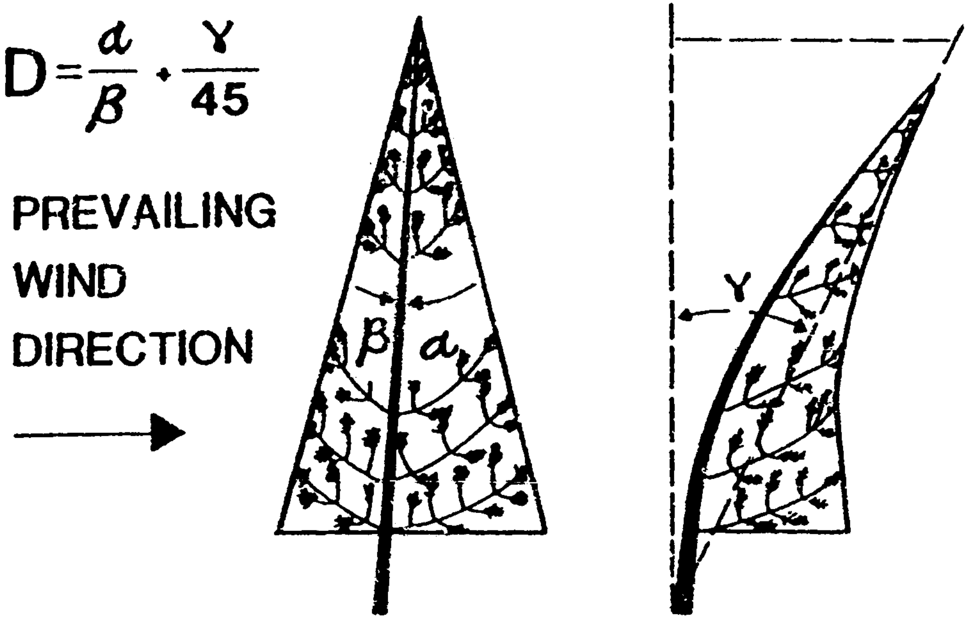


Figure 2. The Deformation Ratio measures the degree of wind induced crown asymmetry and tree trunk deflection. The ratio of α and β has a minimum value of 1 and a maximum value of 5.

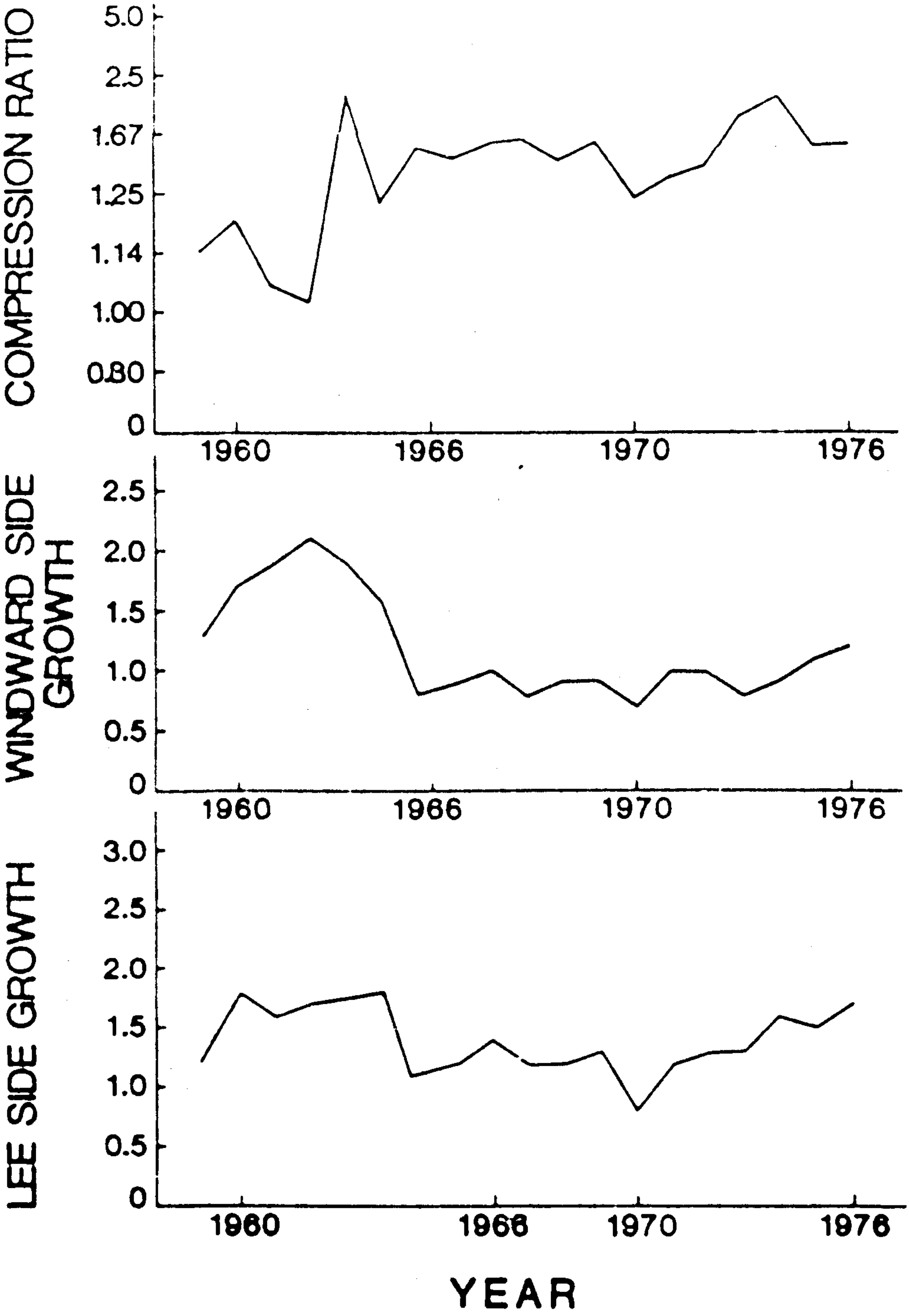


Figure 3. Shows a comparison of windward and leeward growth rate on a coniferous tree. The ratio of the two is called the Compression Ratio and measures the influence of wind on radial growth rate.

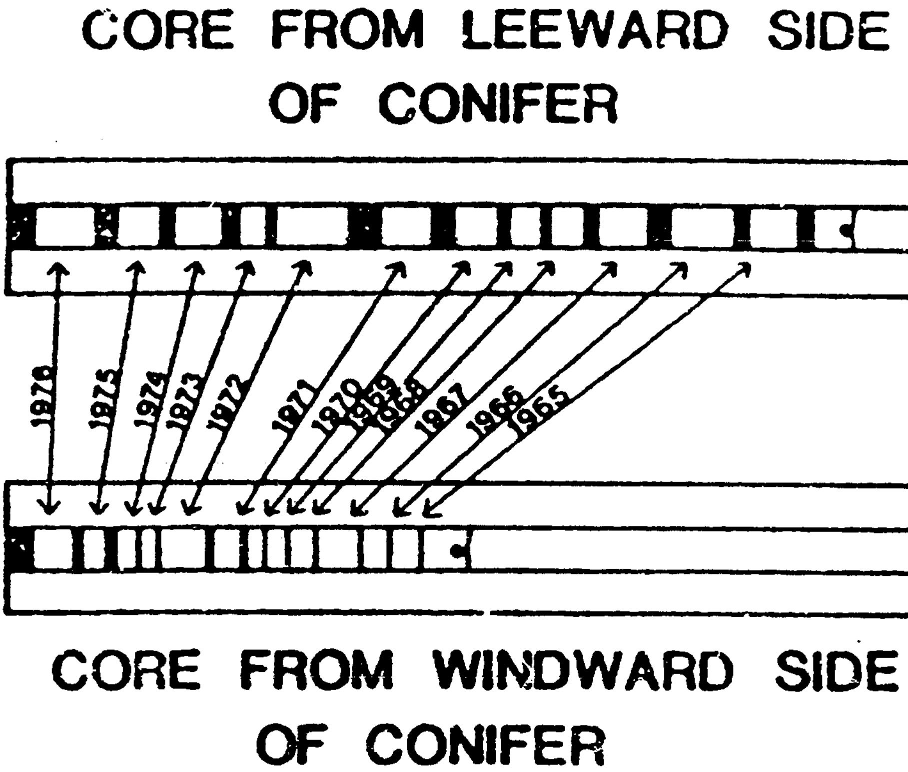


Figure 4. Tree cores are mounted, cross dated and then measured for annual growth increment on the windward and leeward side. Rings on the leeside are wider, and there is a greater proportion of latewood (darkwood). The wider rings are due to compressive stresses on the leeside causing the vertically aligned cells to be shorter and wider.

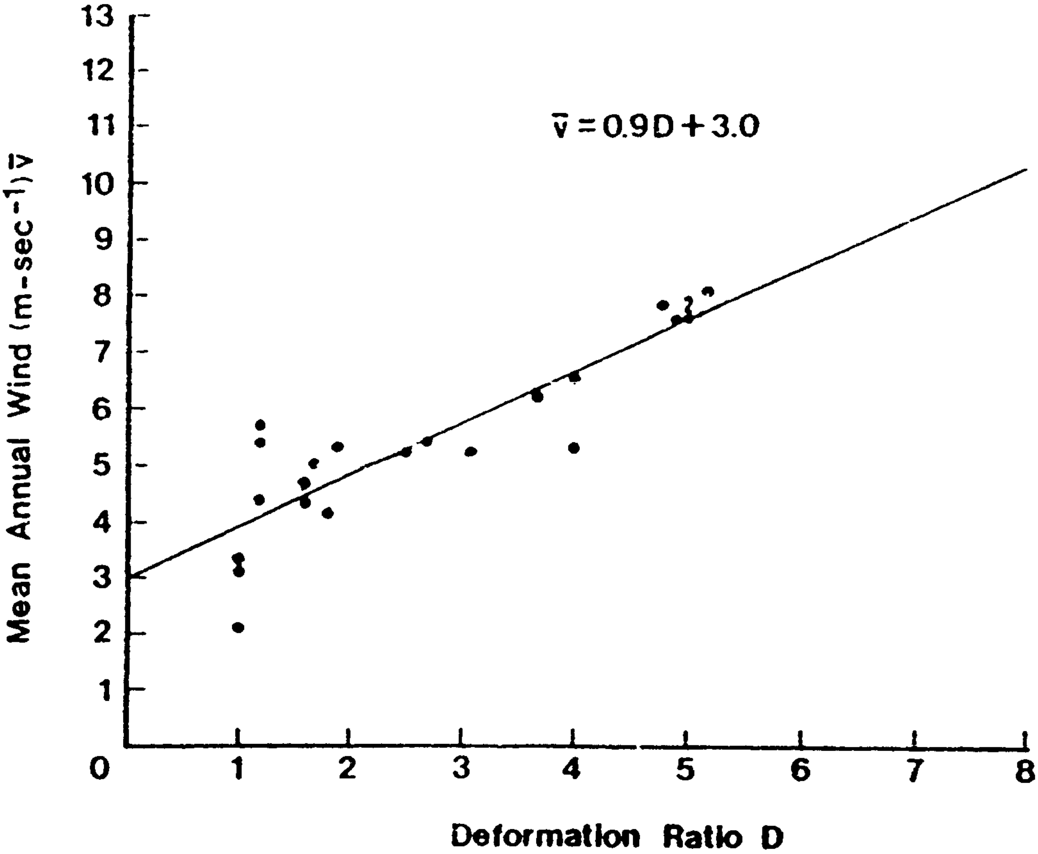


Figure 5. The relationship between the mean annual wind velocity and the Deformation Ratio.

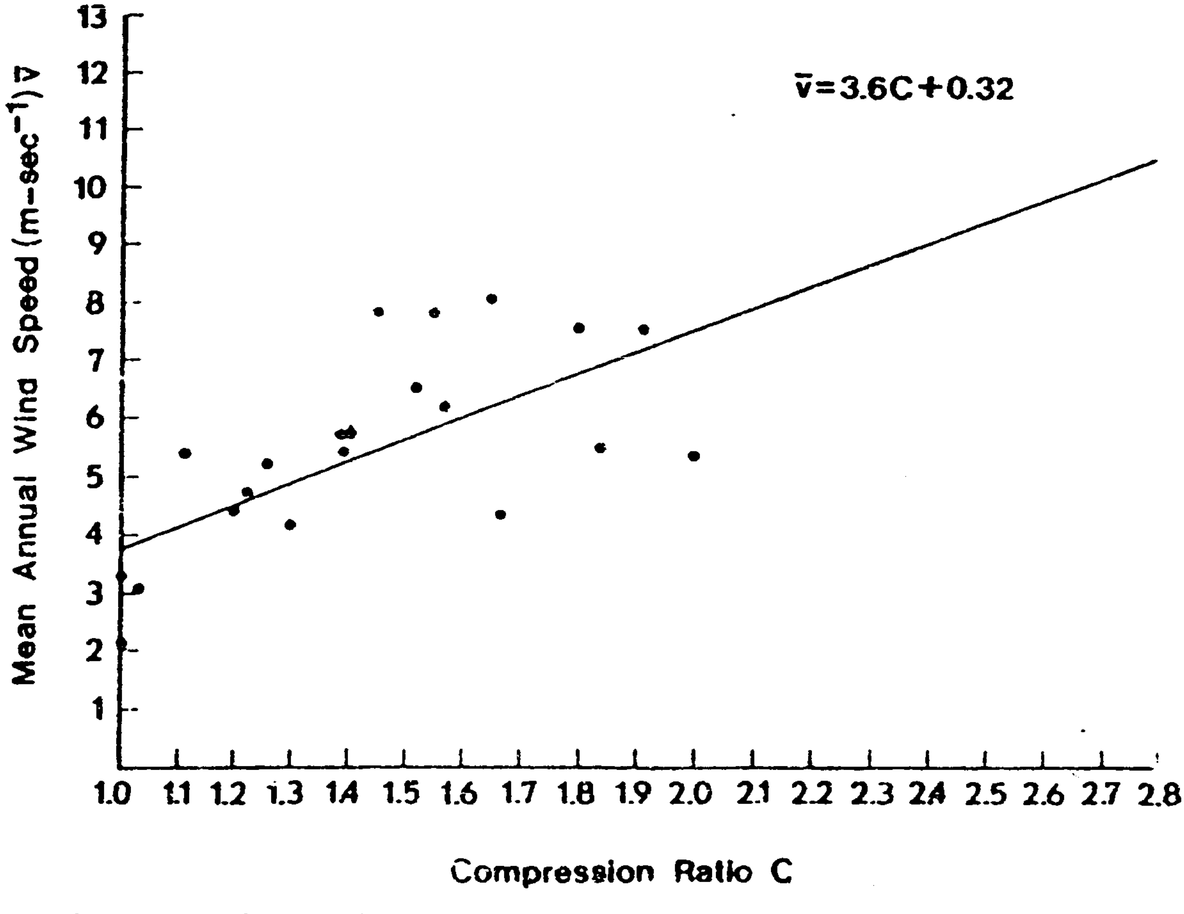
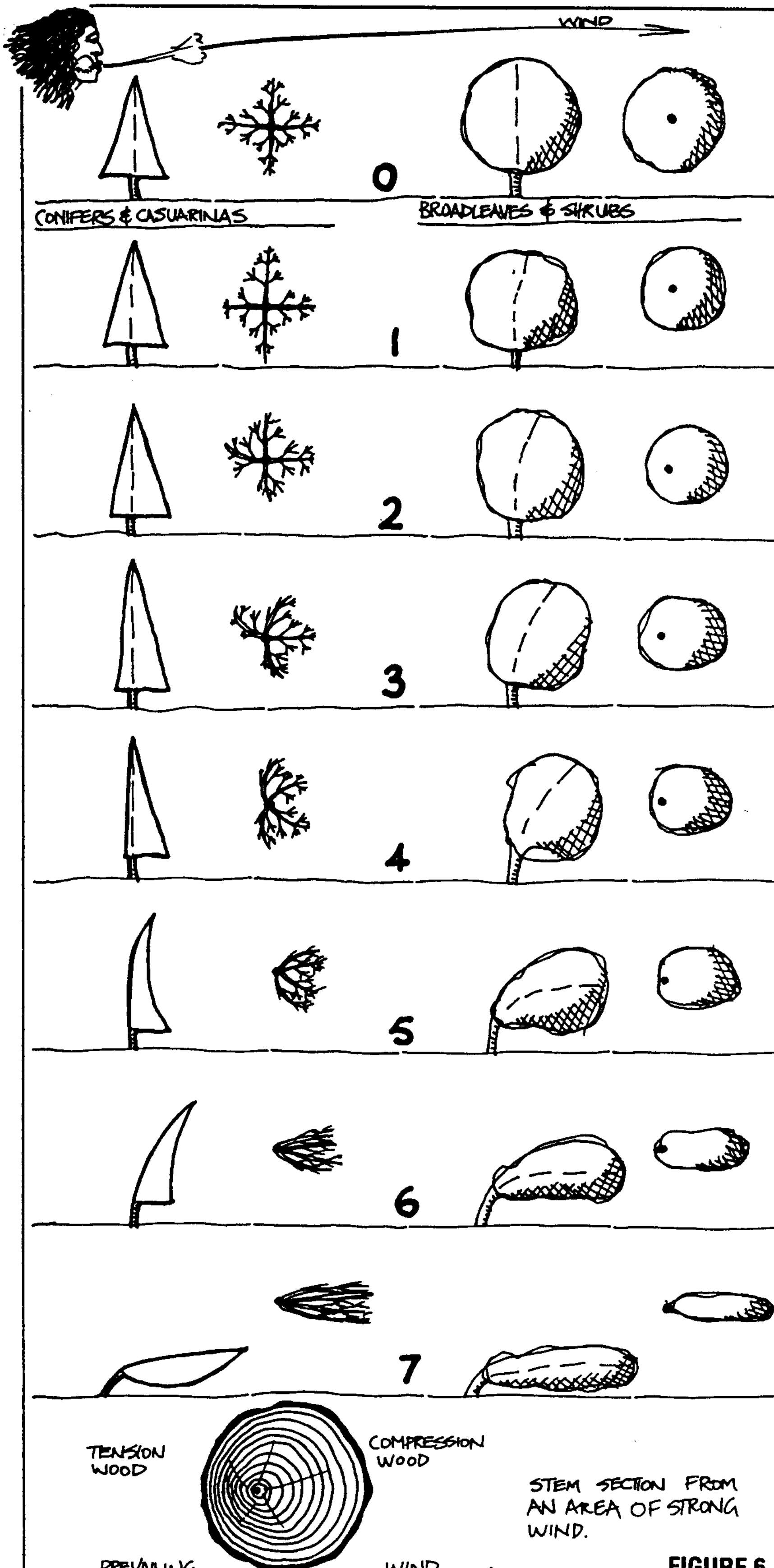


Figure 6. The relationship between the mean annual wind velocity and the Compression Ratio.

GRIGGS AND PUTNAM INDEX



0
NO EFFECT
No deformations of branches

1
BRUSHING
Branches or needles bent away from prevailing winds. Crown slightly deformed.

2
SLIGHT FLAGGING
Small branches bent. Tree markedly asymmetric.

3
MODERATE FLAGGING
Larger branches bent away from the wind.

4
STRONG FLAGGING
All branches swept to leeward. Tree a "banner".

5
PARTIAL THROW
Trunk bent to leeward but vertical near ground.

6
COMPLETE THROW
Trunk now quite bent to leeward.

7
CARPETING
Tree a creeping shrub–like layer of prostrate growth.

THE ABOVE EFFECTS ARE STANDARD FOR TREES NOT AFFECTED BY SALT, ICE, OR SNOW LOAD.

FIGURE 6.2
WIND EFFECTS ON TREES
As winds cross tree lines they are deflected in a new direction. Trees deform or "flag" permanently in prevailing strong winds and can be used to assess the effects of such winds; they form a site–record of wind history.

WIND SPEEDS & DESCRIPTION.

Description	Speed knots	Mean speed knots	Beaufort force	MPH	km/h	m/s	Weather forecast
Calm	< 1	0	0	0.5	1.0	0.2	Calm
Light air	1-3	2	1	2.3	3.7	1	Light
Light breeze	4-6	5	2	5.7	9.3	2.6	-
Gentle breeze	7-10	9	3	10.4	16.7	4.6	-
Moderate breeze	11-16	13	4	15.0	24.0	6.7	Moderate
Fresh breeze	17-21	19	5	22.0	35.2	9.8	Fresh
Strong breeze	22-27	24	6	27.6	44.5	12.4	Strong
Near gale	28-33	30	7	34.5	55.6	15.4	-
Gale	34-40	37	8	42.6	68.6	19.0	Gale
Strong gale	41-47	44	9	50.6	81.5	22.7	Severe gale
Storm	48-55	52	10	60.0	96.4	26.8	-
Violent Storm	56-63	60	11	69.0	111.2	31.0	-
Hurricane	64-71	68	12	78.3	126.0	35.0	-

RELATIONSHIP BETWEEN GRIGGS-PUTNAM INDEX [G] & ANNUAL MEAN WIND SPEED [V] - IN m/sec.

G	V [m/sec]	MPH	W/sq.m. #	Batelle Class *
0	< 3	< 7	< 50	0
1	3 - 4	7 - 9	50 - 80	0 - 1
2	4 - 5	9 - 11	80 - 125	1 - 2
3	5 - 6	11 - 13	125 - 250	2 - 4
4	6 - 7	13 - 16	250 - 400	4 - 6
5	7 - 8	16 - 18	400 - 600	6 - 7
6	8 - 11	18 - 25	600 - 1600	7 - 9
7	> 11	> 25	> 1600	9 - 10

See also:

A: Trees as Indicators
of Wind-power Potential.
J. Wade, W. Hewson
USA 1979

B: Siting Handbook for
* Small Wind-energy
Conversion Systems.
[PNL-2521 Rev. 1.]
Nat. Tech. Info. Service
USA Dept. of Commerce
Springfield VA 22161 USA

C: Wind-Atlas computer-
program.
RISØ National Laboratory
Roskilde Denmark

\# Measured at standard
height of 10 m.
[at 50 m. height =>
a: wind speed + 26 %
b: energy + 100 %].

APPROXIMATE WIND SPEED ENERGY EFFECTS:

A: < 2.5 m/s => Slight effects, no damage to crops or structures.

B: 4.5 - 6.5 m/s => Damage to very susceptible species.

C: 9.5 - 12.5 m/s => Mechanical damage to crops, some damage to structures.

D: 15.5 - 35.0 m/s => Severe structural & crop damage. Damage to some windmill types & models. [Most useful wind-turbine electrical energy is produced in wind-sectors B. and C. - However an Australian model can produce useful electricity at app. 2.5 m/sec.].

REDUCTION OF WIND VELOCITY IN FORESTS:

Penetration in meters:	Remaining velocity in % :
30 m.	60 - 80 %
60 m.	50 %
120 m.	15 %
300 - 1,500 m.	Negligible wind.