Vegetation as an Indicator of High Wind Velocity

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Published by:
Department of Atmospheric Sciences
Oregon State University
Corvallis, OR 97331 USA

Paper copies are $ 2.00.

Available from:
Department of Atmospheric Sciences
Oregon State University
Corvallis, OR 97331 USA

RLO 2227-77-2
UC-60

VEGETATION AS AN INDICATOR OF HIGH WIND VELOCITY

PHASE I

FINAL REPORT

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PREPARED FOR THE UNITED STATES

DEPARTMENT OF ENERGY
DIVISION OF SOLAR ENERGY
FEDERAL WIND ENERGY PROGRAM

DOE CONTRACT NO. EY-76-2226

NOTICE

ACKNOWLEDGEMENTS

This research was prepared for the U.S. Energy Research and Development Administration, under Contract No. EY-76-2226. We would like to extend special recognition to Mac Kim, a work-study graduate student, for his work on this research.

We would also like to thank those people who are collecting wind data for us in this study, included are Jim Curry, Bill Kearney, Janice Stixrude, Art Koerber, Mike Byrn, Dennis McCarthy, Bill Schwartz, Carol Douglas, Ginger Thompson, Wayne Eshelman, George McNab and Jay Steel.

Computer programming is provided by Jim Buckley and administrative support has been furnished by Diane Waters, Barbara Rossbacher, Leah Riley, and Becky Boster. Sincere thanks are extended to these individuals.

ABSTRACT

The objective of this study is to develop methods of using wind deformed vegetation for the selection of optimum sites for utilization of wind energy. Five different indices of wind effects on trees have been developed and are presently being calibrated in terms of various wind characteristics. In addition wind shaped coastal shrubs are being investigated as indicators of persistent strong winds. Field studies are presently being conducted in the Columbia Gorge and in western Oregon. Considerable effort has been devoted to the development of a complete reference list concerned with wind deformed vegetation. Particularly useful references have been abstracted and presented in an Appendix.

The results up to this point indicate that three of the five indices of wind effect on trees appear to be good indicators of the mean wind speed. Among the factors affecting the response of these indicators are exposure, slope and species of the tree. A preliminary analysis using the limited wind data available indicates that the indices are more sensitive to the mean wind from the prevailing direction than to the mean wind from all directions. In this case contact anemometers, which are being used extensively in this study, may not provide sufficient information for calibration of the indices.

The results from the analysis of the effects of wind on the depth of coastal salal are inconclusive up to this point. A technique of using shoot number and length may provide more quantifiable results.

TABLE OF CONTENTS

APPENDIX A

APPENDIX B

I. INTRODUCTION

Wind constitutes a large and practically untapped source of clean, replenishable energy. One of the major obstacles to utilization of this energy resource has been the cost. Up until now the cost of wind energy conversion has been high compared to that of fossil fuels. However, due to the escalating costs of fossil fuels, wind energy conversion systems are becoming cost competitive and, when integrated with hydropower would already be cheaper than oil-fired generation in certain areas of the United States. The effective utilization of these wind resources requires that the best sites be readily identified.

One of the problems in determining wind power potential is the absence of actual wind data in locations believed to have strong winds. Since power is proportional to the cube of the wind speed, it is crucial to know the strength of the winds at sites being considered. The development of quick and inexpensive methods for site selection is essential for wind power to be broadly competitive with conventional energy resources. A promising possibility is the use of biological indicators in site selection for wind energy conversion systems.

A study sponsored by the Energy Research and Development Administration is now underway at Oregon State University to investigate the use of plants as indicators of strong winds. The research up to this point has focused on wind shaped trees and the shrub salal as indicators of high winds. The objective of this research is to calibrate in terms of wind speed, wind deformed vegetation in order to permit location of potential wind power sites without the necessity for elaborate wind measurement programs. This report will summarize the scope, methods and results of the first year of research.

II. SCOPE

The research activities have been concentrated in two areas, the Columbia Gorge and in western Oregon. Fifteen experimental sites have been established along the Columbia River as shown in Figure 1. In western Oregon five experimental sites have been set up (see Figure 2): three in the Coast Range and two on the Oregon coastline. At each experimental site wind data is being collected simultaneously with vegetation data. These field studies have been accompanied by an extensive literature search which will continue through the next contract period. This research is summarized briefly below.

a. Studies of Wind Effects on Trees

i. Definition of the Indices

Five indices of wind effects on trees have been developed and are being tested to determine the relationship between the index value and wind characteristics. Each index provides an easily obtainable, non-dimensional number which when calibrated will yield an approximation of the characteristic of wind responsible for the effect on trees. A definition of each of these indices follows.

Eccentricity (E) An indicator of the departure from circularity of the trunk of a tree. Eccentricity is defined as E, where:

$$E = \frac{(A^2 - B^2)^{\frac{1}{2}}}{A}$$

2A = major axis of the tree
2B = minor axis of the tree

See also Fig. 3.

Shape Index (S) A measure of the relative influence of wind on radial and apical trunk growth. The ratio is calculated by dividing the circumference of the tree at 1.5 m by its height (See Figs. 4,5,6, and 7).

Griggs-Putnum Type Deformation Rating (G) A subjective rating scale similar to that developed by Putnam (1948). Each tree is given a rating based on the characteristics of its wind deformation (see Fig. 8).

Deformation Ratio (D) An indicator of the degree of wind induced flagging of a tree. A ratio of angle α (the angle between the crown and the trunk on the leeward side of the tree) and angle β (the angle between the crown and the trunk of the windward side of the tree) is calculated as in Fig. 9.

Compression Ratio (C) An indicator of the influence of the wind on the formation of reaction wood. The ratio is calculated by taking the annual increment of growth of the bole or trunk on the leeward side of the tree and dividing it by increment of growth of the bole on the windward side of the tree (Fig. 10).

ii. Background for Development of these Indices

Eccentricity is a ratio which defines the degree of departure from circularity. The eccentric growth of tree rings, with wider rings on the lee side of the tree, has often been observed in nature. Bannan and Bindra (1970) found an eccentricity in the cross section of trunks of several coniferous species which could not be ascribed to differential insolation. They found the major axis to be in the direction parallel to the prevailing winds. Similarly in Europe, Barsch (1963) found an average ratio of 1.17 for the diameter in the direction of the prevailing winds to that in the perpendicular direction. Jacobs (1954) firmly guyed tall pines and found the ring increment to be uniform along the boles while unguyed trees developed eccentric growth. These results provided the framework for the index of eccentricity.

Thinning to reduce stem density has become a common forestry practice and as a result, more attention is being focused on stem form development in thinned and unthinned stands (Yerkes, 1960; Lohrey, 1961, Groman and Berg, 1971). Yerkes found that thinned Douglas-fir had greater diameters than the unthinned controls. According to Carlton (1976), wind sway was probably responsible for increased diameter growth along with increased insolation, improved soil moisture and improved rooting.

Another effect of wind on trees is dwarfing. Wind increases transpiration by removing humid layers of air near the leaf or needle surface. The taller the plant, the more subject it is to desiccation by the wind. As a result, the height growth of a tree is reduced in areas with strong wind. The reduced height and increased stem diameter of trees exposed to strong winds was the basis for the shape index.

There have been a number of studies of the deformation of vegetation by wind including Putnam (1948), Barsch (1963) and Yoshino (1973) who have classified trees by the degree of deformation. Wind deformed vegetation may occur any place where the prevailing winds are strong. Coastal areas, river valleys, and mountainous regions have all been the subject of ecological investigations into this phenomenon.

Coastal Areas Because of the high winds which occur over many ocean areas, coastal regions have been observed to be particularly subject to tree deformation and other wind influences on vegetation. General discussions on coastal vegetation have been prepared by Oosting and Billings (1972) and by Oosting (1954), but because the effects of wind blown salt spray on coastal plant communities are difficult to distinguish from those of high winds alone, attention has also been devoted to the analysis of salt spray influences on coastal vegetation (see Boyce, 1954; Edwards and Holmes, 1968; Malloch, 1972; and Boerner and Forman, 1975).

River Valleys Certain river valleys experience high winds, such as the Rhone Valley of France (Barsch, 1963), and the Columbia River Gorge of the Pacific Northwest (Lawrence, 1939). Lawrence found two types of flagging common in the Columbia Gorge. In the west end of the Gorge, trees have a ragged tattered appearance. Most of the large branches project in a westerly direction. On the east side of the tree, branches appear to be pruned. Strong east winds occurring with freezing rain were proposed as the cause of this type of deformation.

Confiers on the east end of the Gorge differ from those in the west; not only in the direction of their asymmetry, but also in the way they appear to be wind trained. The trunks are bowed toward the east and the branches are bent in the same direction.

Mountain Regions Strong winds occur regularly in many mountainous regions. The flagged trees on Whiteface Mountain in New York's Adirondack Mountains were studied by Holroyd (1970) using both the direction of branch growth and the position of reaction wood (abnormal wood structure induced by wind stress) in the trunk tops. Wind instruments placed at various locations on the mountain during the summer recorded the same prevailing wind directions as indicated by the trees. The author mentions that the degree of flagging might be calibrated to obtain wind speed, but he did not attempt to do so. Studies of tree flagging in the subalpine zone of Japan have been conducted by Yoshino (1973) and in the Ajdovscina Region of Yogoslavia by Yoshino (1973) and by Yoshino et al. (1973). There has been no attempt in any of these studies to correlate wind speeds and the degree of flagging.

The indices G and D which are indicators of wind induced changes in the form of the crown of a tree are being related to wind speeds measured at each location in our study.

Mayhead (1973) investigated the drag coefficients of a number of trees in a wind tunnel and found that they vary significantly but the drag coefficient decreases sharply with increasing wind speed. Our research has shown that Ponderosa Pine are deformed to a lesser extent than Douglas-fir between 2 - 6 m sec^{-1} but above that speed both show equal deformation reflecting the decreasing importance of the difference in drag coefficients between the two species.

As discussed earlier, trees exposed to strong unidirectional winds exhibit eccentricity in the width of their growth rings. "Such eccentricity is usually associated with particular characteristics in cell anatomy and is designated reaction wood" (Fritts, 1976). The reaction wood which appears at the lee side of the tree is called compression wood. The rings with compression wood are wide and contain a larger proportion of late (dark) wood than the rings on the windward side of the tree. The reaction wood in coniferous stems may be attributed to lateral redistribution or asymmetric production of a growth regulating substance, a growth inhibitor, or an auxin-destroying enzyme (Fritts, 1976).

Another theory regarding tree stem development is called the "beam of uniform resistance". This theory postulates that a tree with a limited supply of woody substance available each year will distribute the wood along the stem so as to equalize the resistance to breakage due to wind sway. McMahon (1975) found that in most trees the diameter of a tree increases as the 3/2 power of the tree height.

Carlton (1976) found in mechanically swayed Douglas-fir that there was a significant increment growth increase in the direction of the sway. The same phenomenon was found in earlier studies by Bannan and Bindra (1973), Barsch (1963), Jacobs (1954), Neel and Harris (1971) and Hall (1969).

Büsgen and Münch (1931) cited examples where longitudinal tension and pressure resulted in no anatomical changes. They concluded differential pressure and tension is required for increased diameter growth and that dynamic stretching and compression of the tissue acts as the growth stimulus.

In many areas, the strongest winds are not during the growing season. This particularly true in the west end of the Columbia Gorge. According to Duffield (1968), the tree must have some sort of memory of the magnitude of non-growing season wind storms so that the stem will form to resist breakage. Fritzche (1933) also discussed a safety factor which would strengthen the stem to resist long return period storms. He reasoned that if no such mechanism were present, there would be selected pressure against the tree's continued survival. These studies of the growth of trees in windy environments provided the background for our compression index which seeks to relate wind speed to the ratio of radial growth on lee side and windward side of the tree.

b. Studies of Wind Effects on Coastal Salal

The effect of wind on the shrub salal (Gaultheria shallon Pursch) is being investigated at Yaquina Head on the Oregon Coast. The growth of salal in four locations on this exposed coastal headland is being measured. At two of the locations the wind speed over the salal has been reduced by 50% by specially constructed screens. Two other unscreened locations serve as control sites. The monthly growth of salal is being monitored by the use of photographs, counts of the number of new shoots and measurements of their length on selected shrubs in an attempt to determine the importance of wind on the growth of these plants.

c. Literature Search

During the past year a considerable amount of time has been devoted to the development of complete reference list of papers, books and reports concerned with deformed vegetation and estimation methods for wind speed and direction using wind shaped trees or plants. A bibliography with nearly 300 references is included in Appendix A. Abstracts of selected references which appear particularly useful are presented in Appendix B.

III. METHODOLOGY

a. The Development of Indices of Wind Effects on Trees

i. Field Studies

The five indices defined above are calculated from data collected in the field. At each experimental site wind data is being gathered so that the relationship between the wind and each index value can be determined. At nine of the locations wind data is being collected by using contact type wind-run anemometers, from which monthly averaged wind speeds can be determined. At three locations temperature in addition to wind is also being measured. 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.

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 height and circumference, major and minor axis of the trunk, and the altitude of the location where the tree is growing. A photograph is taken from a spot perpendicular to the direction in which the tree is flagged for later laboratory analysis of the degree of wind flagging. The tree is then cored on the side facing the prevailing wind direction at breast height, 1.5 m; a core is also taken from the opposite side of the tree trunk. The holes in the tree are plugged and the cores are mounted in blocks and labeled for laboratory analysis. All the data is recorded on an encoded data sheet (see Fig. 11).

Dendrometer readings on a scheduled basis are taken on the windward and leeward side of the tree to determine the difference in diameter growth rate. The dendrometer is a standard dial micrometer gauge mounted in a metal frame. Three screws are driven into the xylem (non-growing wood) on both the windward and leeward side of the tree; these screws form a plane not affected by current growth. The base of the dendrometer is placed against the screws and the distance between the screws and the bark is measured. Dendrometer readings are greatly affected by moisture stress in the trees and negative growth readings may occur. To obviate this problem, readings are taken as near as possible to the same time of day and wet bulb and dry bulb temperatures are measured so that inferences of the relative amount of moisture stress can be made.

On a limited number of trees, core samples and dendrometer readings are taken from the sides of the tree perpendicular to the prevailing wind direction. These readings are taken to validate the hypothesis that wind is the factor causing a differential in the increment of growth between the windward and leeward side of the tree.

The final step in the field analysis may include the collection of needles, bark and a cone so that positive species identification can be determined if necessary by a dendrologist. Up to the present time the study has concentrated on Douglas-fir (*Pseudotsuga menziesii*) and Ponderosa Pine (*Pinus ponderosa*), but also includes Noble Fir (*Abies procera*) and Sitka Spruce (*Picea sitchensis*). Future studies will include deciduous trees and shrubs.

ii. Analysis of Field Data

The wind data is processed in the Wind Power Research Laboratory 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 is processed and the indices defined earlier are calculated. Tree cores are sanded, polished and sent to the Forest Science Laboratory for tree ring analysis. The data on the tree rings is cross dated, as shown in Fig. 12, to insure that the rings on each side of the tree are aligned and represent the year assigned. Compression ratios are calculated for each year by taking the increment of growth on the windward side and dividing it by increment of growth on the leeward side. In addition an average compression ratio is calculated to give an index of the wind's effect on the tree integrated over the life of the tree.

Statistical relationships will be developed between each of the index values and wind speed or some characteristic of the wind regime which is responsible for the tree deformation. At the present time complete wind data for more than a year is available at only eight of the nineteen locations. Vegetation data is presented in Table I.

b. Analysis of the Importance of the Mean Wind Speed to the Physiological Characteristics of Coastal Salal.

Field studies on the effect on wind on salal have commenced at Yaquina Head on the Oregon Coast. To test the hypothesis that wind is the environmental factor that most affects the depth of the salal, the following experimental program has been set up. In one location a screen 120 cm wide and 90 cm high was placed perpendicular to the prevailing northerly summer winds in a patch of salal. The purpose of the screen was to reduce the wind speed sufficiently so that comparisons could be made between the growth of salal behind a screen and salal growth where the wind flow is unobstructed. Two sets of screens were set up in another spot to obstruct both north and south winds from a patch of salal. This screen is 180 cm wide and 90 cm high. The wind flow behind the first screen and between the other two screens is measured with a contact type wind-run anemometer which gives the average wind speed over the period of observation, whether it be a minute or a year. As a control, another contact anemometer was placed in an unscreened patch of salal. Near each patch of salal growth stakes were driven into the ground and photographs were taken on a monthly basis from four camera mount locations. In addition three branches were selected and marked for analysis of new shoot number of length. One branch was chosen from each screened area; two branches were selected in unscreened areas. These branches were diagrammed and buds were counted and measured; as the season progressed the buds bloomed, and became new branches.

V. RESULTS

a. Wind Effects on Trees

Since only short series of wind data are available to date, a meaningful comparison of index values and wind speeds is not yet possible. Strongest winds are expected to occur at Augspurger Mountain, Seven Mile Ridge, Ortley Ridge and Cape Blanco. The limited wind data available for these locations indicates annual average wind speeds are greater than 7.5 m sec^{-1}. Areas expected to have lower winds include Dallesport, Wasco, Corbett, Wren and Larkwood Meadows. The six-year average wind speed at Dallesport is 3.6 m sec^{-1}. Limited data from the other four locations indicates average winds of less than 4 m sec^{-1}. Those indices which best reflect the difference in winds between these locations are G, D and C with the exception of one C value at Corbett. The E and S indices also show high values in strong wind areas but seem to be less sensitive and vary more between trees at the same location. The indices S, E and C are also strongly affected by other factors such as: species and age of tree, slope of the land, and competition from other trees for food reserves. Slope and competition appear to be particularly important factors affecting the shape ratio and eccentric growth as indicated by the eccentricity and compression ratios. The effect of slope on eccentric growth is well documented but the mechanism by which a tree adds this reaction wood is less certain. In deciduous trees reaction wood or wide rings are on the uphill side of the trunk and termed tension wood. In conifers reaction wood is found on the downhill side of the trunk and referred to as compression wood. The mechanisms that could cause reaction wood include asymmetric auxin production, growth inhibitors or auxin destroying enzymes.

Competition will result in eccentric shaped boles if growth in one or more quadrants is affected by competition for light and nutrients. Trees in open areas or thinly populated stands will also generally have larger circumferences for the same height than trees in more densely populated stands.

Among the things we have learned in our research thus far include:

* Exposure of the trees to wind may vary over the life of the tree and therefore the analysis of indices for a dominant tree in stand of trees is more complex than the analysis for an isolated tree.

* Competition for light and food reserves has a strong influence on all indices but particularly on C, E, and S. Isolated trees should be analyzed as a separate data set from trees in a forest.

* Slope seems to be an important factor affecting the formation of reaction wood, eccentric growth and the relationship of height and circumference. In future analyses an attempt will be made to filter out this effect.

* Species and age influence the response of each index to the wind. In Ponderosa Pine, the response of the values of Eccentricity seem more sensitive to the wind speed than the values for Douglas-fir. Compression ratios in young trees vary more than those of mature trees.

* It appears that trees may be more responsive to the average wind speed from the prevailing direction than the average wind from all directions. If this is true, contact type wind-run anemometers may not provide sufficient information for our study.

These results are promising but we will need more data and more detailed wind information particularly from locations which have long term wind records.

b. Wind Effects on Coastal Salal

The results of the research conducted thus far on wind effects on salal are inconclusive. Analysis of photographs taken over the four-month period from April - July 1977 indicated a slight increase in plant growth but almost no difference in growth between screened areas and unscreened areas could be detected. The plants behind the large screen appeared to have the largest increase in growth (about 3 cm). The other locations had detectable growth but less than 3 cm. The growth stakes had 3 cm increments.

Since the errors in taking and interpreting the photographs are likely to be large compared to the growth of the salal, it appears doubtful the measuring of growth using photographs will be successful.

A different technique of evaluating growth was also tried. Analysis of shoot length and number indicated an average increase of shoot length of just over 3 cm and an overall decrease of shoot number over the four month period.

There was very little difference in shoot length between the screened and unscreened areas (see Table II). The data indicated that shoot length increased slightly more in the open spots than in the screened sites and there was a net decrease in shoot number in the open or control locations.

At this point, it would be difficult to conclude anything from these results except that using shoot length and number gives more analyzable data than photographs which may have errors caused by inaccurate camera positioning and errors in photographic interpretation.

Recently, the topmost leaves of the salal in open areas have turned brown on the top. The salal behind screens does not seem to be as affected as those plants which are not shielded. This scorching by wind, salt or some other factor may affect growth during the reminder of the growing season and could provide more clues as to the affect of screens by September.

Table I. Index data collected for 28 conifers in Oregon and Washingon

Tree Identifier	Location	Altitude	E	S	D	Direction of Flagging	C	G
151	Stevenson, WA	110 m	0.45	.09	1.3	W	1.22	2
161	Crown Point	218 m	0.43	.09	5.9	SW	1.54	7
162	Crown Point	218 m	0	.11	6.7	SW	1.57	7
381	Augspurger Mtn.	1010 m	0.20	.09	8.3	SE	1.74	4
382	Augspurger Mtn.	1040 m	0.37	.12	2.6	E	1.75	4
383	Augspurger Mtn.	1010 m	0.32	.07	5.9	E	1.92	4
401	Lyle, WA	20 m	0.40	.10	1.8	E	2.2	3
402	Lyle, WA	20 m	0.49	.07	2.5	E	1.44	3
491	Corbett	225 m	0.66	.10	*	WSW	1.47	2
492	Corbett	225 m	0.36	.10	1.8	WSW	1.25	2
501	Mosier Kaiser Ranch	220 m	0.28	.11	1.2	E	1.31	2
512	Cathlamet Hills	333 m	0.36	.10	2.5	E	1.27	3
511	Cathlamet Hills	333 m	0.24	.12	2.6	E	1.31	3
541	Wind Mountain	293 m	0.31	.06	4.0	SE	1.34	3

Table I - continued

Tree Identifer	Location	Altitude	E	S	D	Direction of Flagging	C	G
551	7 Mile Ridge	710 m	0.41	.11	3.9	E	1.95	4
552	7 Mile Ridge	710 m	0.45	.11	3.5	E	2.0	4
561	Wren	140 m	0.28	.09	3.5	NE	1.17	1
571	McCulloch Peak	610 m	0.30	.08	3.0	SE	1.13	3
591	Larkwood Meadows	670 m	0.20	.06	1.7	E	1.6	2
592	Larkwood Meadows	670 m	0.58	.08	1.7	E	1.34	2
601	Wasco	660 m	0.34	.08	1.7	E	*	2
611	White Salmon Ridge	530 m	0.23	.06	1.4	ENE	1.68	3
621	High Prairie	612 m	0.47	.11	5.3	E	1.13	3
662	Ortley Ridge	620 m	0.25	.09	7.4	E	2.18	4
661	Ortley Ridge	715 m	0.40	.08	3.7	ENE	1.78	4
651	Cape Blanco	10 m	0	.11	4.0	S	*	7
641	Prairie Mtn.	1050 m	0.24	.13	2.0	N	1.24	3
631	Dallesport, WA	80 m	0.24	.09	1.8	E	1.46	2

* Missing data

Table II. Data for Yaquina Head experiment on wind effects on coastal salal.

Date	Site	Average Wind Speed m/sec	Average Shoot Length cm	Shoot Number
12 May 1977	Screen #1	.8	2.4	8
12 May 1977	Screen #2	.8	.9	11
12 May 1977	Open #1	1.6	1.9	6
12 May 1977	Open #2	1.6	1.3	8
08 June 1977	Screen #1	.6	2.8	8
08 June 1977	Screen #2	.4	3.2	9
08 June 1977	Open #1	1.2	6.3	6
08 June 1977	Open #2	.8	4.2	7
06 July 1977	Screen #1	1.1	6.1	10
06 July 1977	Screen #2	2.1	3.7	10
06 July 1977	Open #1	2.6	5.4	6
06 July 1977	Open #2	4.0	5.5	6

Net increase in shoot length and number:

Screened sites	68%	0.5
Open sites	69%	-1.0

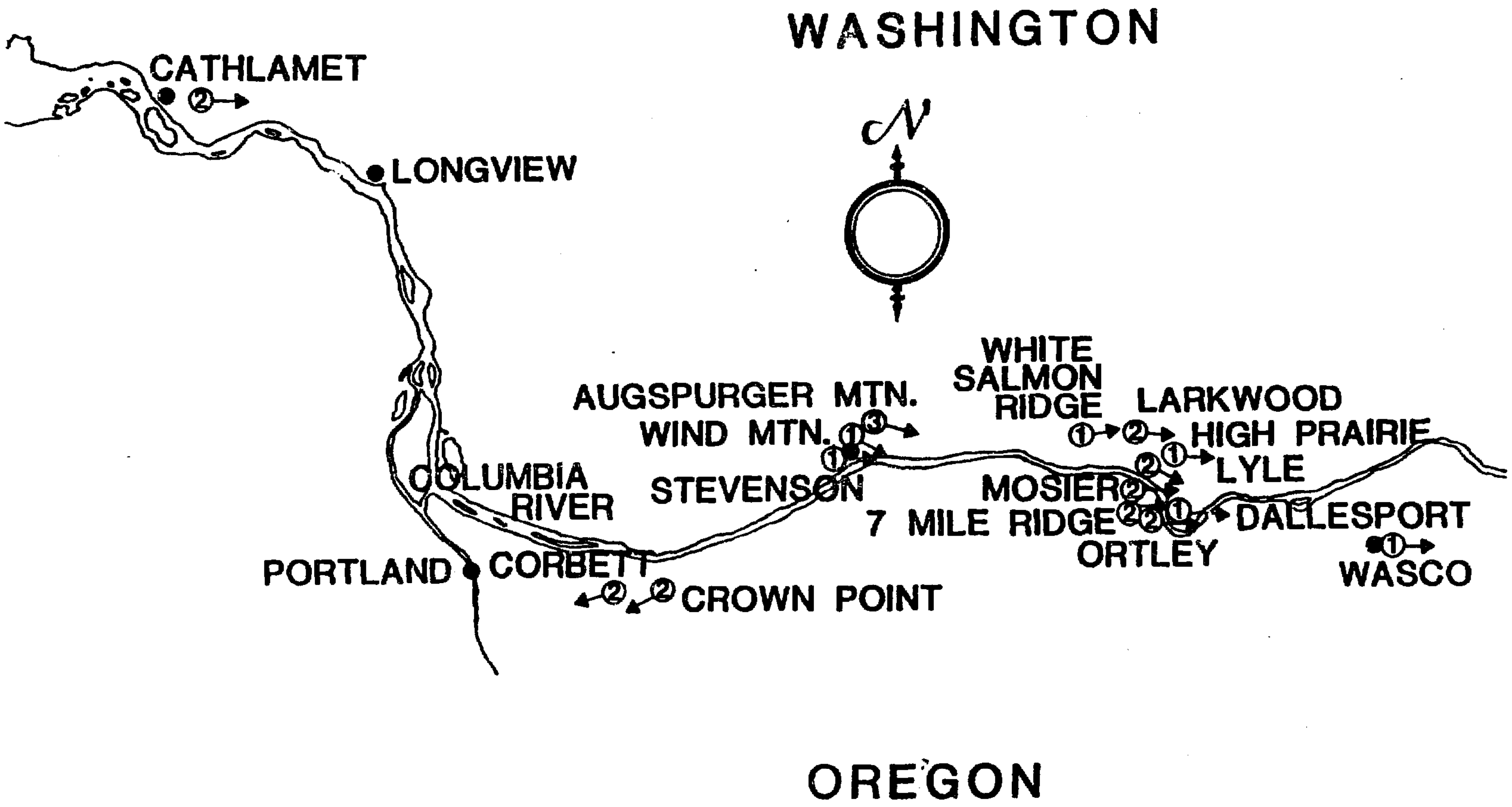


Figure 1. Biological wind prospecting locations along the Columbia River. Numbers inside the circle denote the number of trees studied at each site. Arrows indicate the direction of the wind as indicated by the flagging.

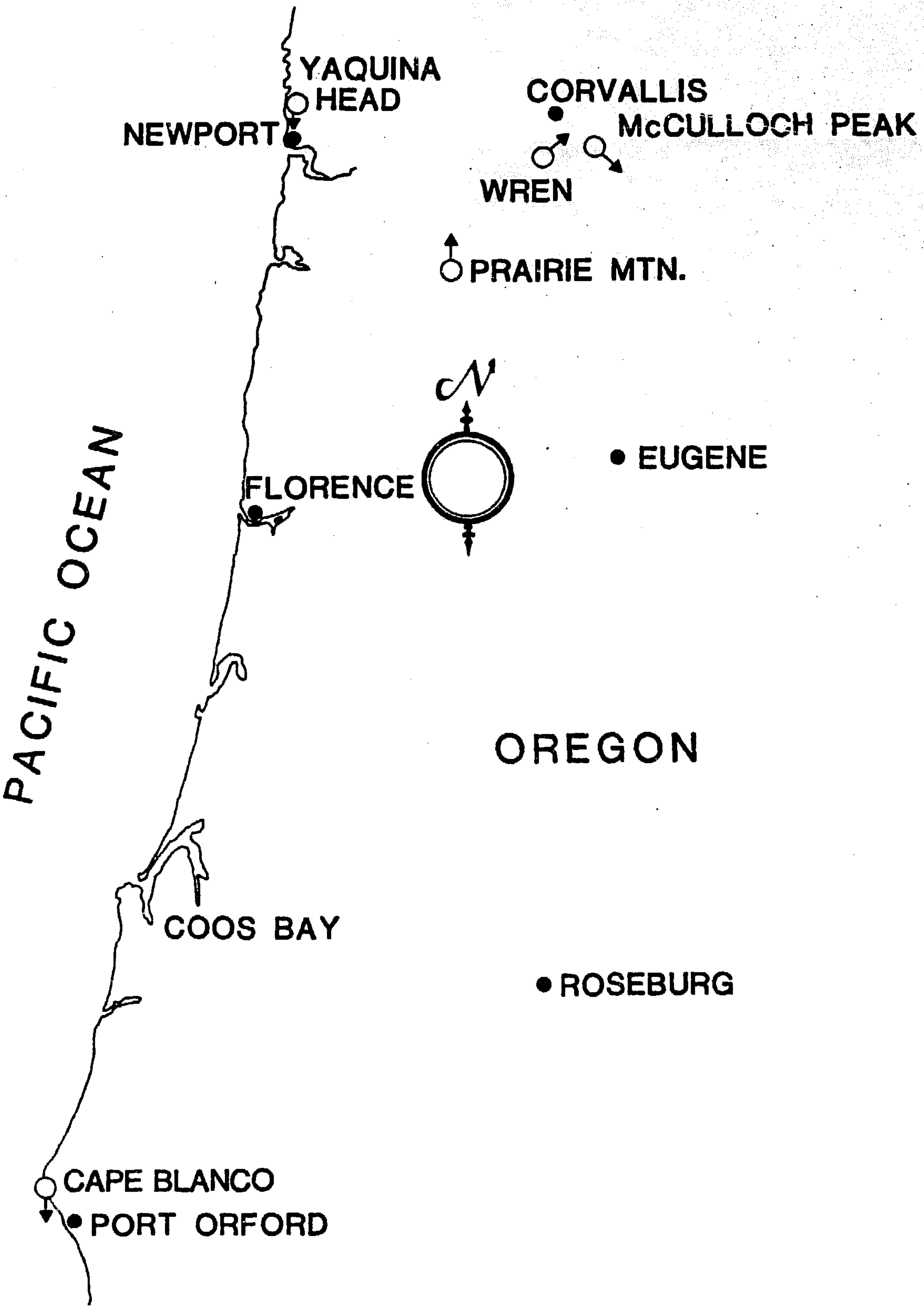
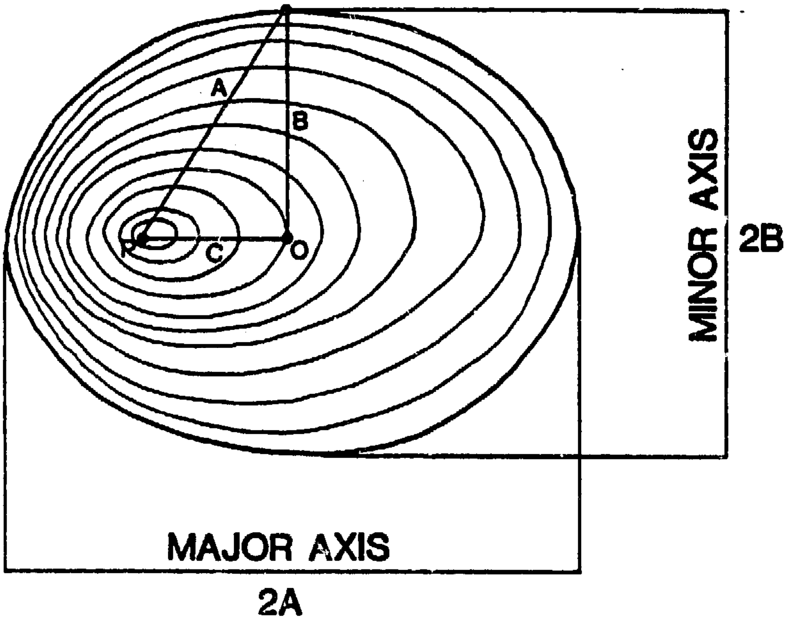


Figure 2. Biological wind prospecting study sites in western Oregon.

DETERMINING THE ECCENTRICITY OF CONIFER STEMS



P = PITH OR CORE
O = CENTER

$$E = \frac{C}{A} \qquad C^2 = A^2 - B^2$$

$$E = (A^2 - B^2)^{1/2}/A$$

Figure 3. The method of determining the eccentricity of the trunk of a tree from the outside involves measuring the length of the major and minor axes with tree calipers.

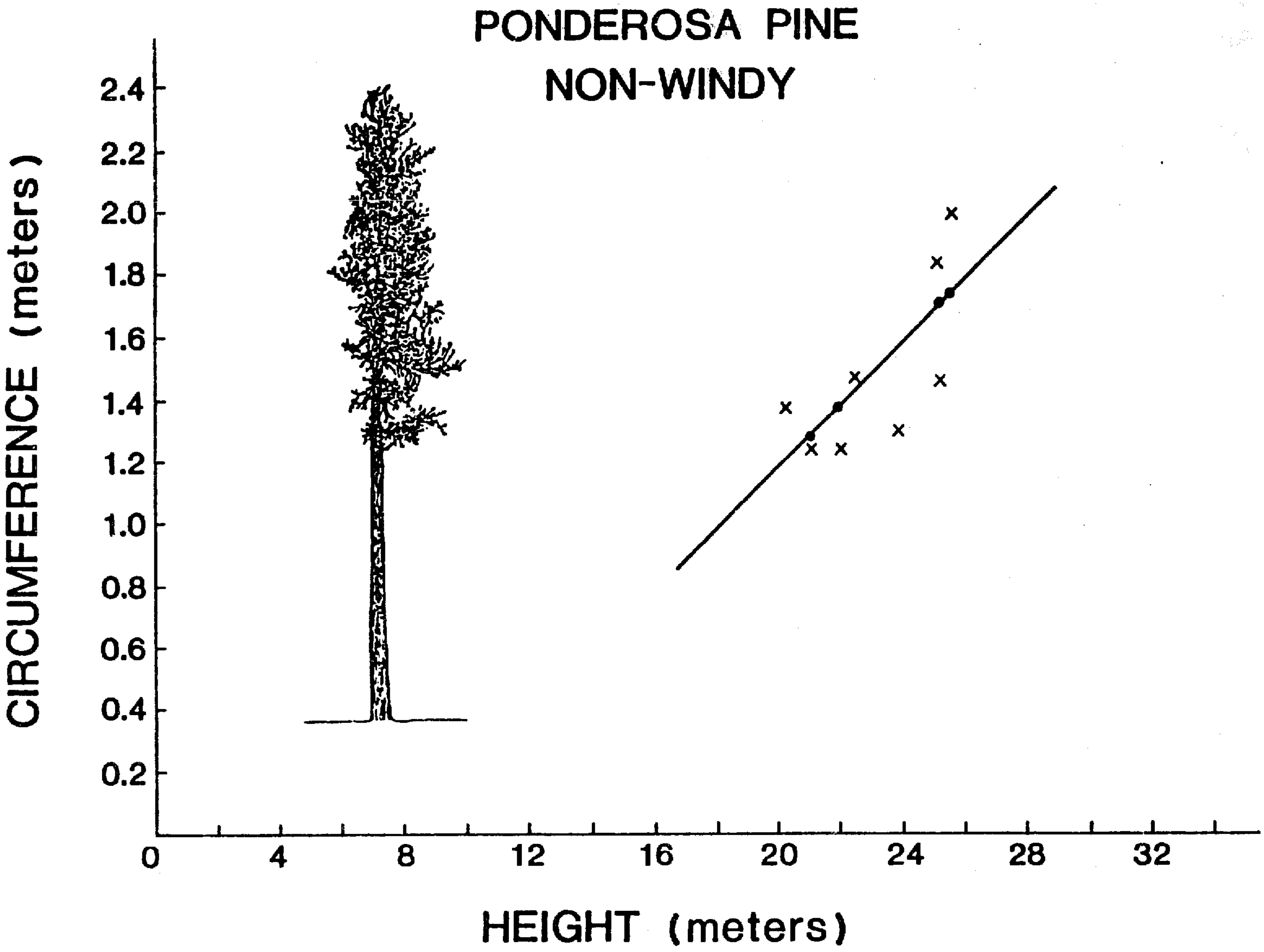


Figure 4. The relationship between height and circumference at a non-windy location.

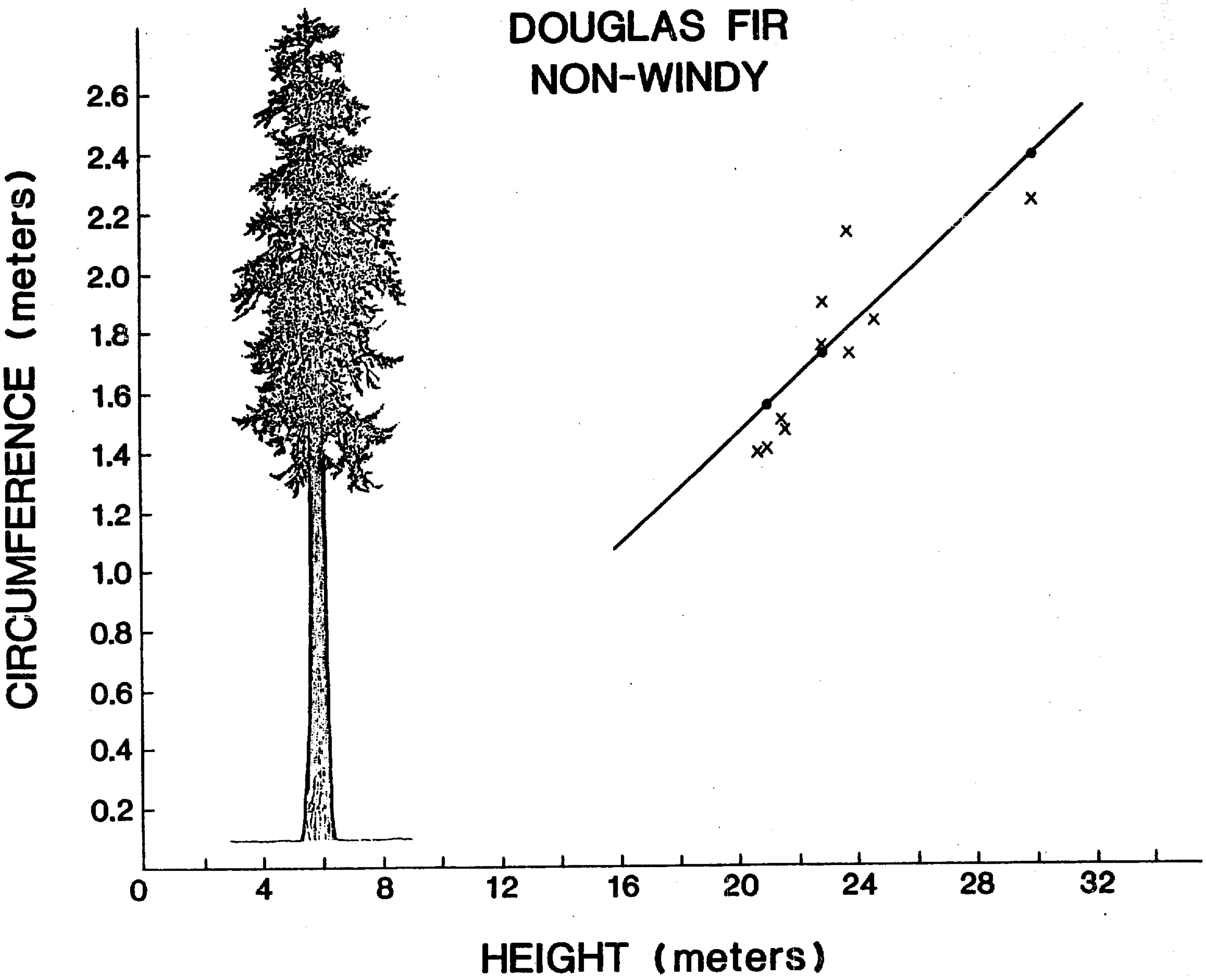


Figure 5. The relationship between height and circumference for Douglas-fir in Corvallis, average annual wind speed 2 m sec^{-1}.

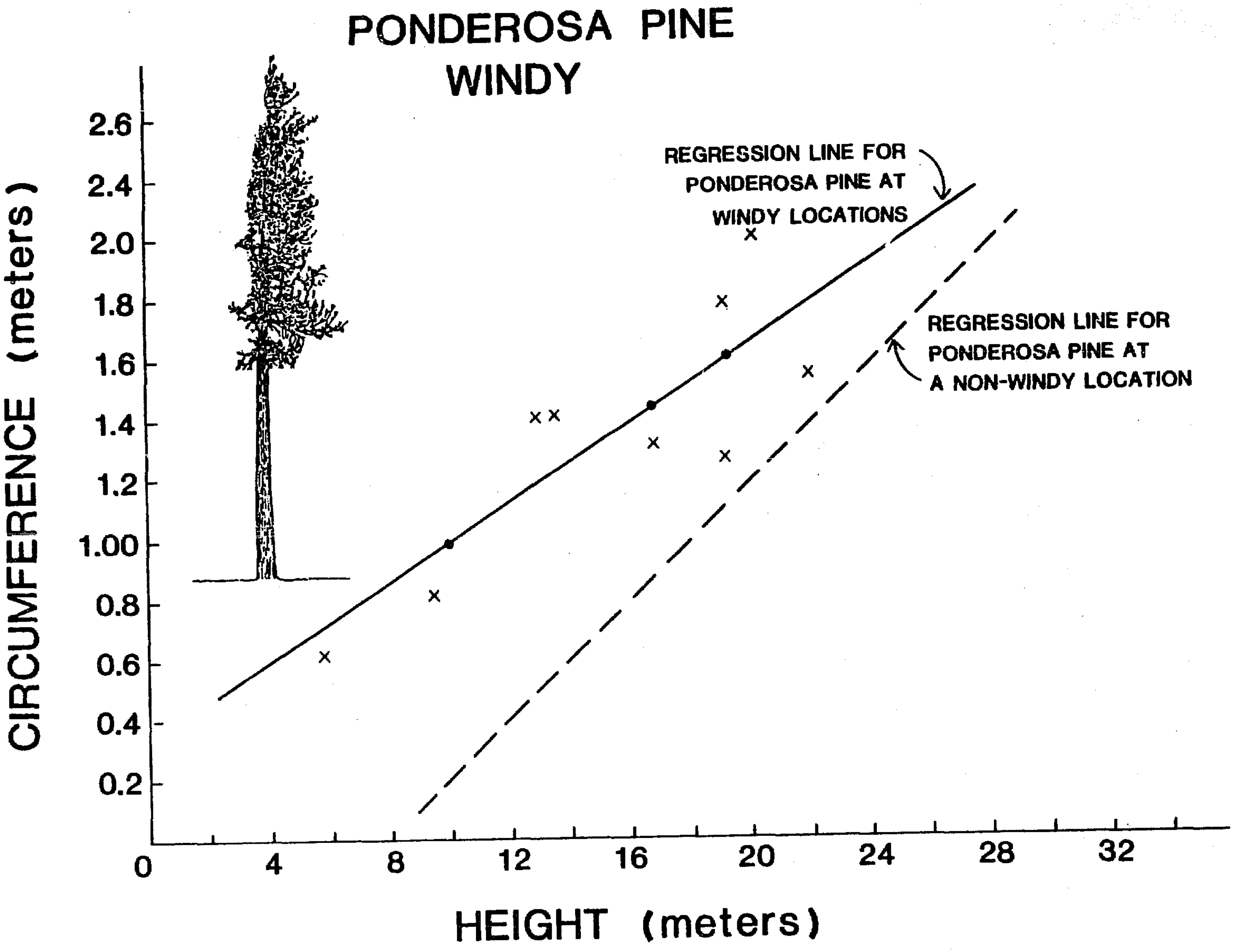


Figure 6. The relationship of height and circumference at biological wind prospecting sites. Note larger circumferences for the same height.

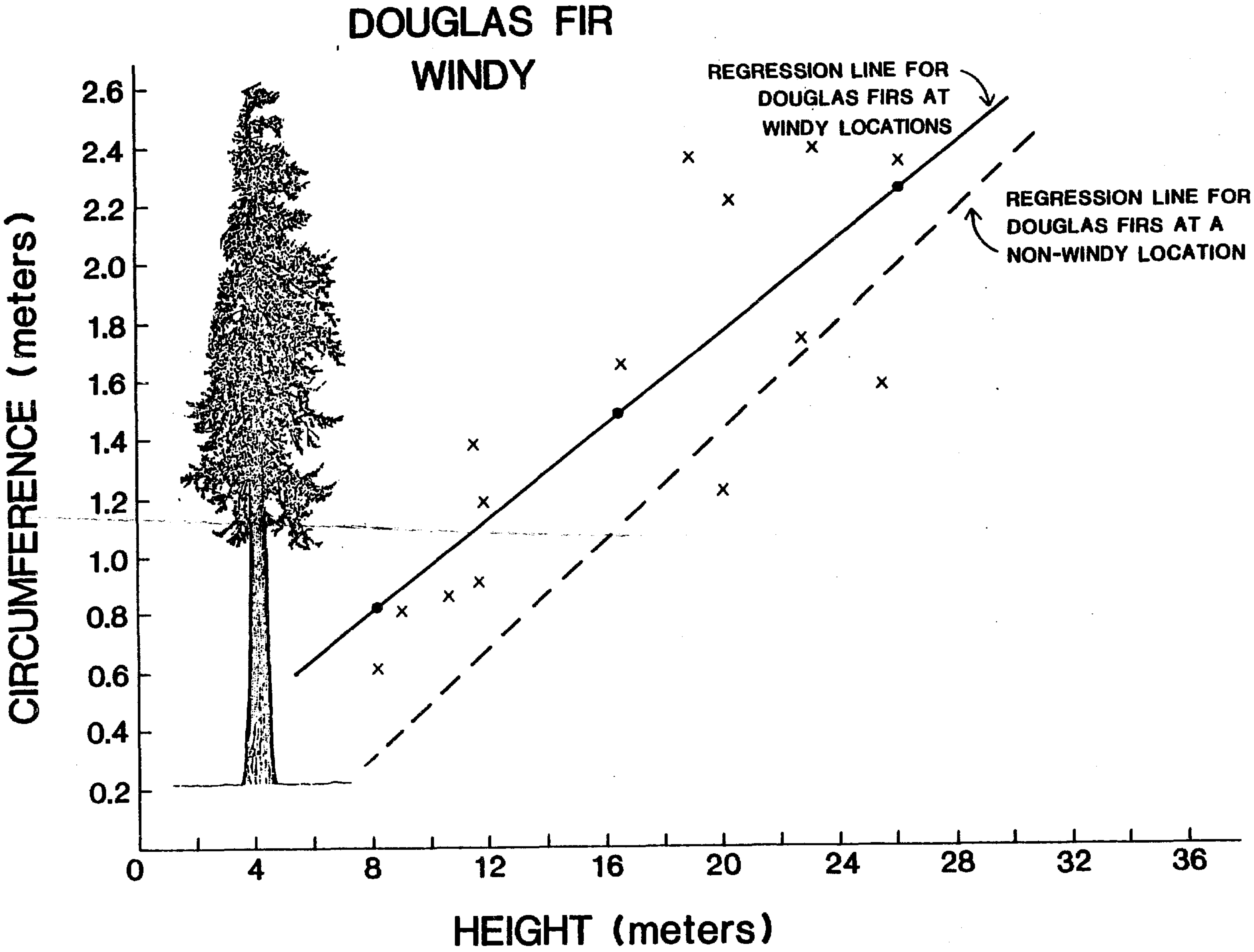


Figure 7. The relationship of height and circumference for 14 Douglas-fir in windy areas.

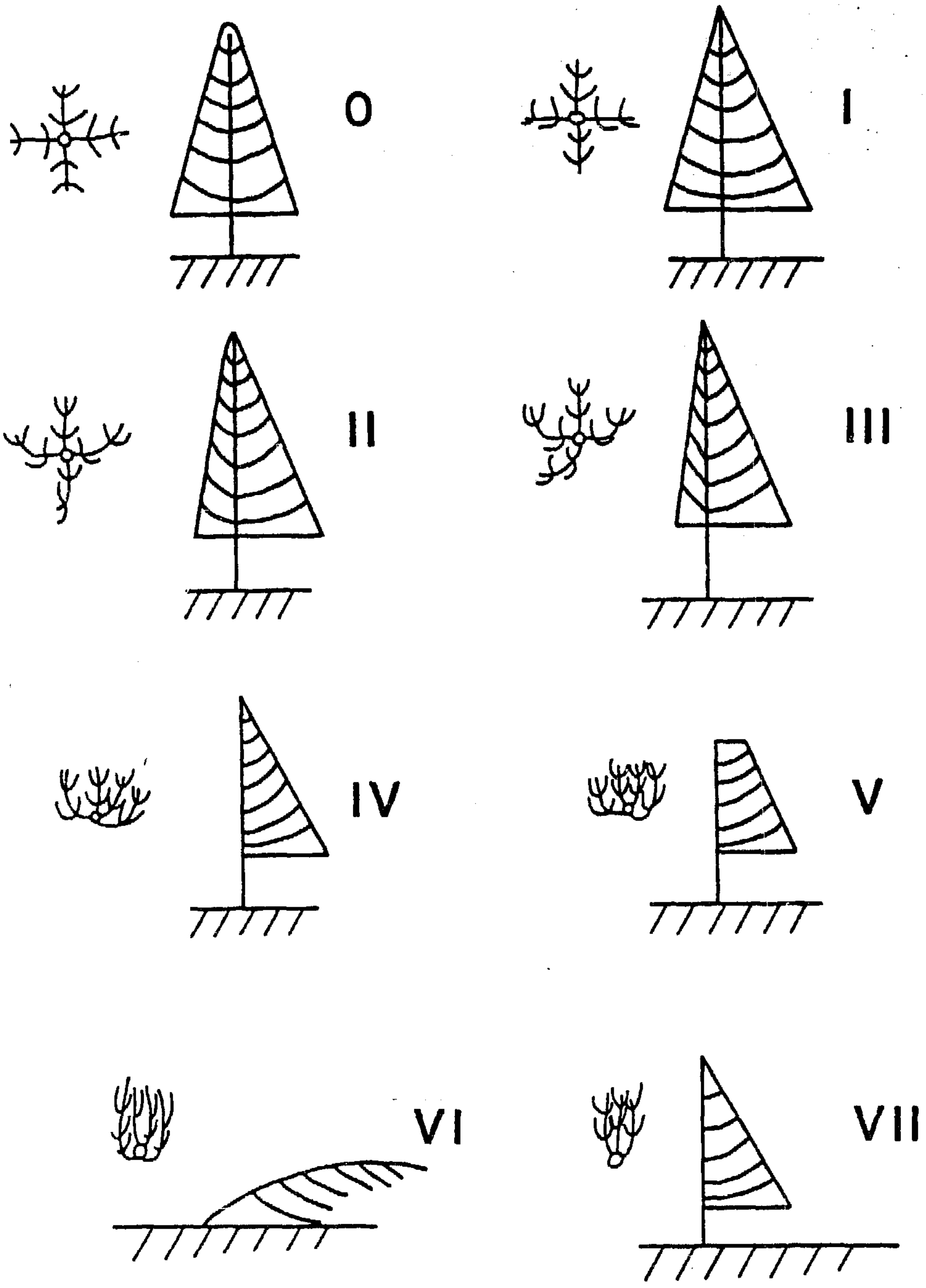


Figure 8. A representation of the rating scale based on the shape of the crown and degree of bending of twigs, branches, and the trunk. Class VII is pure mechanical damage.

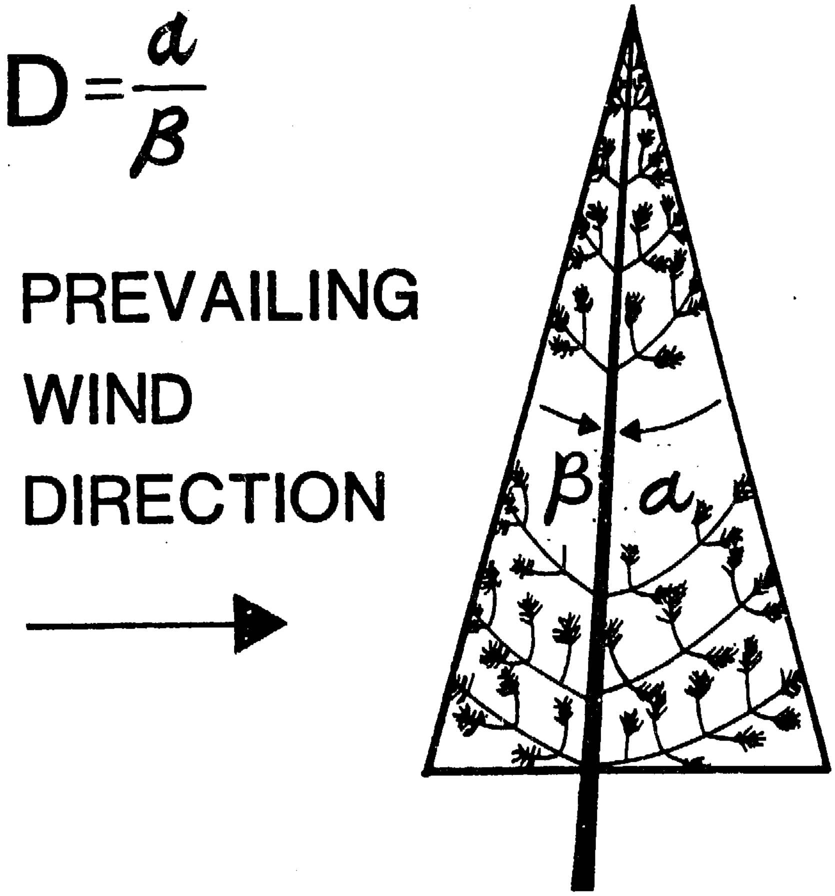


Figure 9. The deformation ratio is based on the degree of flagging of the crown.

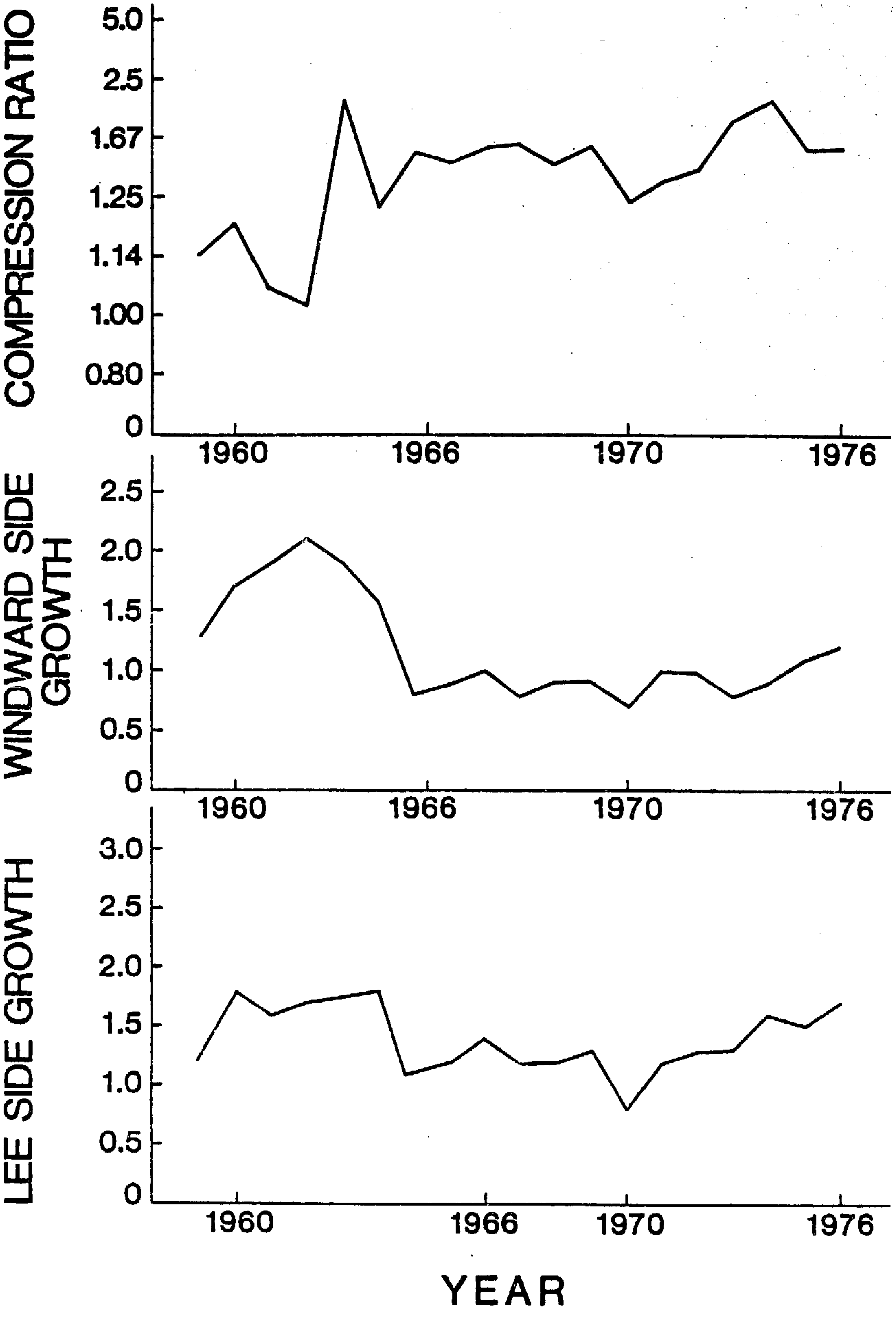


Figure 10. Compression ratios are calculated for each year from ratios of leeward to windward growth.

FIELD SURVEY FORM FOR VEGETATION STUDY

TREE IDENTIFER

DATE

SPECIES OF TREE

GEOGRAPHIC LOCATION

ALTITUDE

CONCITION OF TREE

DIMENSIONS OF MAJOR & MINOR AXIS

HEIGHT OF TREE

CIRCUMFERENCE (BREAST HEIGHT)

DIRECTION OF FLAGGING

RELATION OF TREE TO SLOPE

NEARBY TOPOGRAPHY

SOIL CHARACTER & DRAINAGE

PROXIMITY OF OTHER VEGETATION

DATE OF LAST RING

DIAGRAM OF CORE SAMPLE
LOCATIONS AND TREE DIRECTION
OF SAMPLES

PHOTOGRAPHS

DATA FOR BEGINNING OF GROWING SEASON DATE:

DRY BULB TEMPERATURE

WET BULB TEMPERATURE

DENDROMETER READING

WINDWARD

LEEWARD

DATA FOR END OF GROWING SEASON DATE:

DRY BULB TEMPERATURE

WET BULB TEMPERATURE

DENDROMETER READING

WINDWARD

LEEWARD

Figure 11. An example of a field survey form used for studies of wind effects on trees.

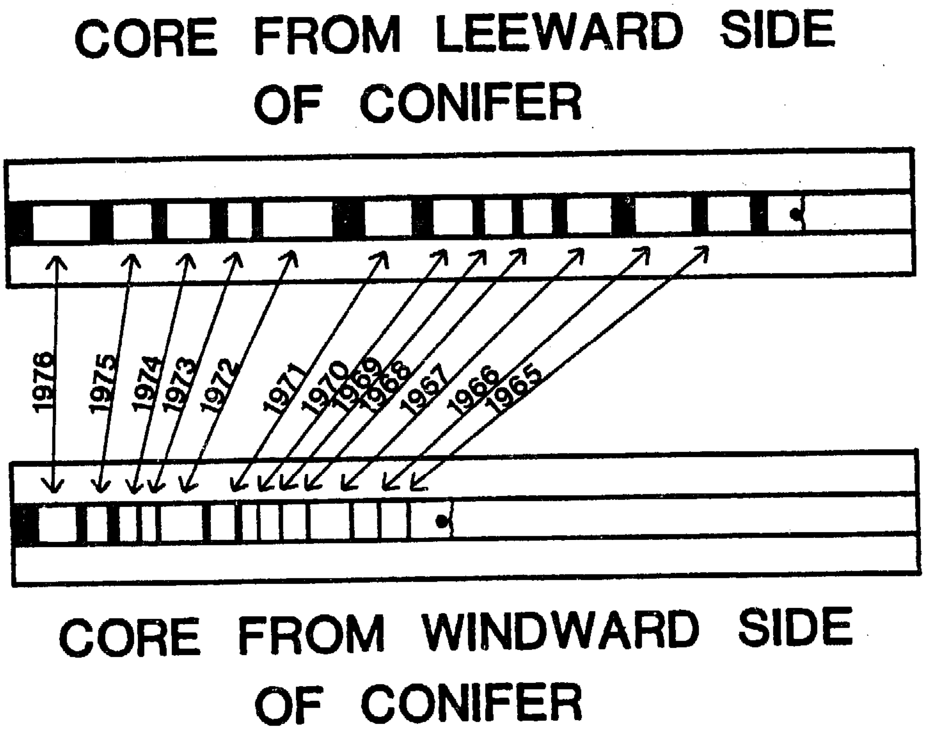


Figure 12. Cores from each side of the tree are carefully checked and cross dated.

APPENDIX A

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including

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and Yoshino (1973)

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CLIMATOLOGICAL NOTES

Department of Geography
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No. 1	1969	Masatoshi M. Yoshino: Climatological studies on the polar frontal zones and the intertropical convergence zones over South, Southeast and East Asia. 71p.
No. 2	1969	Isao Kubota: Distribution of mean monthly precipitable water in the Northern Hemisphere and its time change. 28p.
No. 3	1969	Iwao Tsuchiya: Selected bibliography on water balance of Monsoon Asia, (I). 28p.
No. 4	1969	Masatoshi M. Yoshino: Maps of monthly mean absolute topography of the 50 mb-level in the Northern Hemisphere, 1956-1965. 120p.
No. 5	1970	Masatoshi M. Yoshino (Ed.): Local climate as a factor forming hindrance of tree growth (Preliminary Report). (in Japanese with English abstract) 65p.
No. 6	1971	Nozomu Kobayashi: Upper air climatology along the east and west coasts in the middle latitudes. 75p.
No. 7	1971	Masatoshi M. Yoshino and Hyoe Tamiya: Maps of monthly mean absolute topography of the 100 mb-level in the Northern Hemisphere, 1956-1970. 180p.
No. 8	1971	Iwao Tsuchiya: Selected bibliography on water balance of Monsoon Asia, (II). 42p.
No. 9	1972	T. Asakura and E. Kitahara: Distributions of specific humidity over the Northern Hemisphere at the 1000, 850 and 700 mb levels for June and July, 1970. 56p.
No. 10	1972	Masatoshi M. Yoshino, Hyoe Tamiya and Minoru Yoshimura: Studies on Bora (I). 78p.
No. 11	1973	Iwao Tsuchiya: Selected bibliography on water balance of Monsoon Asia, (III). 22p.

APPENDIX B

Abstracts of Selected Papers Useful in Study of Wind Effects on Trees

Barch, D., 1963: Wind, Baumform and Lanschaft: Eine Untersuchung des windeinflusses auf Baumform and Kulturland schaft am Beispiel des Mistralgebietes im franzosischem Rhonetal. In: Freiburger Geographische Hefte, Heft 1, edited by F. Bartz and W. Weischet. Freiburg.

An excellent and thorough paper on the problem of tree deformation by the wind. A subjective index of wind effects of trees is developed. No attempt is made to calibrate this index. There is an excellent bibliography on European research with 121 references.

Bannan, M.W. and M. Bindra, 1970: The influence of wind on ring width and cell length in conifer stems. Canad. J. Bot. 48: 255-259.

This report deals with some of the relationships between wind, stem form, ring width, cell length and frequency of multiplicative divisions in the cambium. Three species were studied: white spruce, lodgepole pine, and eastern white pine. In this study, the annual rings were found to be narrow on the west side of the stem and widest on the east side where the prevailing wind is from the west. The authors concluded that in these kind of sampled trees, the wind seems to be more potent than sun in the determination of stem form. The differences in cell length for the opposite sides of the stem could not be related to a consistent one sided development of reaction wood. However, the development of shorter cells is favored due to the widening of the ring on the leeward side.

Carlton, R.R., 1976: Influences of the duration of periodic sway on the stem form development of four-year-old Douglas-fir (Pseudotsuga menziesii). unpublished Masters Thesis, Oregon State University.

This paper describes the effects on growth of mechnically induced sway. Significantly, Carlton found that stem diameter increases as the period of swaying increased. The bibliography contains a good collection of recent papers on wind effects on trees.

Fritts, H.C., 1976: Tree Rings and Climate. Academic Press, London.

This book summarizes the basic principles currently employed in dendroclimatology and illustrates how these concepts and principles are applied to the reconstruction of climatic variation that has occurred in the past. This book is not addressed to the problem using trees as an indicator of winds but provides excellent source of information on the effect of other climatic and environmental variables on tree growth.

Heiligmann, R. and G. Schneider, 1974: Effects of wind and soil moisture on black walnut seedlings. For. Sci. 20: 331-335.

This study is concerned with the influence of different combinations of typical wind velocities and soil moisture regimes on the growth of black walnut seedlings. High wind velocity reduced stem, foliage, shoot and root dry weights. A significant influence to growth of trees is caused by constant wind velocity is the conclusion of the article.

Holroyd, E.W. III, 1970: Prevailing winds on Whiteface Mountain as indicated by flag trees. Forest Science, 16, 222-229.

The direction of prevailing winds was determined by the study of flag trees on Whiteface Mountain in the New York Adirondack area. Using both the direction of branch growth and the position of the reaction wood in the trunk tops, a very complex wind pattern was found. Tree-flagging indications of the wind should be very useful, when combined with a topographic map, the direction of the wind will show regions of rising or subsiding air. Tree-flagging can show areas of exposure to strong winds and the drying associated with them.

Jacobs, M.R., 1936: The effect of wind on trees. Austral. For. 1: 25-32.

The purpose of this article is to discuss the means of preventing the unnecessary damage which is caused by wind on trees and the observations of wind damage on trees. When any tree is subjected to a force which continually acts in one direction such as a prevailing wind, it puts on uneven annual rings which change its normal circular cross section to an elliptic with the long axis running down the wind. Wind acting on the higher center of gravity of the crown of the high crowned tree has a greater turning moment than in the case of deep crowned trees.

Jacobs, M.R., 1954: The effect of wind sway on the form and development of Pinus radiata. Austral. J. Bot. 2: 35-51.

Free swaying trees grew more in diameter over the lower part of the trunk than stayed trees. The effect of sway at the height of 4 ft was greater in a very heavily thinned test area than in a well-stocked test area. Sway caused increased growth of roots near the trunk and increased eccentric trunk development along the line of main winds. The height growth of stayed trees was little different from that of the free swaying trees, but height/diameter relationships were changed. After two years, trees that had been prevented from swaying were no longer stable in a normal environment.

Jacobs, M.R., 1939: A study of the effect of sway on trees. Austral. Commonw. For. Bur., Bul. No. 26. 17 pp.

This paper describes the experiments designed to determine the effect of sway on tree growth. Two kinds of trees, P. radiata and E. gigantea were chosen as samples, four test plots were set up in different stands, and these test plots were compared to others acting as controls. The whole idea of this study was to prevent the tree sway and this prevention of sway caused marked reduction in diameter growth in the lower part of the bole.

Larson, P.R., 1965: Stemform of you Larix as influenced by wind and pruning. For. Sci. 11: 412-424.

Unidirectional and multidirectional winds from oscillating electric fans were applied to a young Larix tree. The size and vigor of the live crown determined mostly the stem form. Exposure to wind caused a pronounced downward shift of increment towards the stem base, usually at the expense of upper stem parts. Prevention of wind sway by staying the trees largely eliminated the downward shift of increment. Height growth of free swaying trees was also reduced, and this reduction was partially offset by staying. Trees responded to unilateral winds by producing eccentric growth on the lower stem consisting of high proportion of reaction wood. However, the increased increment on the lower bole of trees exposed to multilateral wind consisted of wood of normal structure uniformly distributed circumferentially.

Lawrence, D.B., 1959: Some features of the vegetation of the Columbia River Gorge with special reference to asymmetry of forest trees. Ecol. Monogr. 9, (2), 217-257.

This paper presents not only an explanation of the effects of wind in the Columbia Gorge but also presents descriptions of the geology, topography, soils, flood history and tributary drainage systems. It describes the two types of tree deformation in the Gorge; the wind trained crowns in the eastern portion of the Gorge and the pruned crowns in the western end of the Gorge caused by strong east winds and heavy ice deposition.

Mayhead, G.J., 1973b: Sway periods of forest trees. Scot. For. 27: 19-23.

The sway period of confiers in a closed canopy is found to increase with increasing tree size. The results from this study support the view that sway period can be satisfactorily expressed in terms of the height, diameter at breast height and mass of the tree. The natural sway period of the tree, the gust frequency distribution of the wind at and approaching, the wind speeds causing windthrow, and the damping properties of the tree, all contribute to windthrow.

Mayhead, G.J., 1973a: Some drag coefficients for British forest trees derived from wind tunnel studies. Agric. Meteor. 12: 123-130.

A wind tunnel was used to determine the drag coefficient of a variety of commerical conifers. The drag coefficients varied within and between species, and with wind speed. Fixed drag coefficients were estimated for use in critical tree height calculations. The practical applications of drag coefficients and critical tree heights are discussed. Some conclusions reached include: Large variations in drag coefficient were found between tree species; relatively large variations in drag coefficient occur both within a genus and within a species; and a sharp reduction in drag coefficient occurs with increasing wind speed.

McMahon, T.A., 1975: The mechnical design of trees. Sci. Amer. 253: 92-102.

Discusses the mechanical design of trees and the relationship between height and diameter of a tree. The diameter of the tree increases as the 3/2 power of tree height according to the model of elastic similarity.

Moss, A.E., 1940: Effects on trees of wind driven salt water. J. Forestry, 38, 421-425.

This paper describes the effect of wind driven salt on trees. Moss found injury only occurred when the tree was exposed to the direct force of the wind.

Neel, P.L. and R.W. Harris, 1971: Motion-induced inhibition of elongation and induction of dormancy in Liquidambar. Science 173(3991): 58-59.

Six of eight Liquidambar trunks were moderately shaken for 30 seconds daily, and they were compared to the unshaken trees for their height growth and terminal buds. An endogeneous mechanism for regulating tree growth in wind situations is implicated. (Formation of reaction wood along with the other growth modifications happens when the prevailing wind applies and blows from one direction for several hours or days toward the tree.)

Opatowski, I., 1946: On oblique growth of trees under the action of winds. Bul. of Math. Biophys. 8: 41-49.

In this article, it is shown that an inclined regular growth of tree trunks under the action of prevailing winds may be explained as a response of the plant to mechnical action of the wind. The mechnical effect of winds on the trunk of trees has substantially two different forms. One occurs when an unusually strong wind bends the tree into a plastic range, so that a very large portion of the tree trunk may acquire the permanently abnormal position, the trunk continues to grow vertically. The other is the oblique growth of the whole tree trunk under the action of prevailing winds. A numerical example of this second effect is developed and results for a palm tree agree with observational data.

Putnam, P.C., 1948: Power from the Wind. New York, Van Nostrand.

Trees are discussed as indicators of wind power potential. Different types of wind deformation are discussed as well as the effect of species and age. Conifers are described as good indicators of wind. This is probably the earliest attempt to use trees as an indicator of wind characteristics.