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Theodolite surveying for nondestructive biomass sampling

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Abstract

By theodolite surveying, the relative location of points in space may be calculated by triangulation. With the aid of computers, data gathered by theodolite surveying may provide a dimensional analysis of individual trees. Because the system is nondestructive, the rates and patterns of change in the spatial structure of trees and stands may be monitored by repetitive surveying. This paper presents a preliminary test of the approach upon trees in a 40-year-old Douglas-fir (Pseudotsuga menziesii) *plantation in western Washington. From experience gained in the initial experiment, recommendations are made to increase the precision of repetitive measurements.*

Introduction

The theodolite is an instrument used in precise surveying to locate points in space by triangulation. The use of high speed computers for converting angle measurements to point locations allows theodolite surveying techniques to be used for describing the physical structure of vegetation assemblages in considerable detail with relative ease. Such a surveying procedure has been used to construct simulation models for studying the effects of vegetation on engineering activities (West et al. 1971). Since the method is nondestructive, it offers the possibility of repetitive sampling with high inherent precision. Exploratory surveys were made recently to test the applicability of the system for this purpose (West and Allen 1971). This paper examines some data from a Douglas-fir stand at the Coniferous Biome intensive site in Washington.

Description of the Surveying System

The procedure requires two theodolites placed at an arbitrary distance apart and located conveniently to the subject trees (fig. 1). The vertical and horizontal angles from each instrument to every point located in the sample space are measured with respect to a base line. The instruments can be moved about to obtain clear lines-of-site to desired points in the sample space and every instrument location (turning point) is referenced to the base line by conventional traverse survey-

Figure 1. Instrument set-up for surveying spatial structures of trees. Two theodolites are in use; the instrument in the middle is a spotting laser.

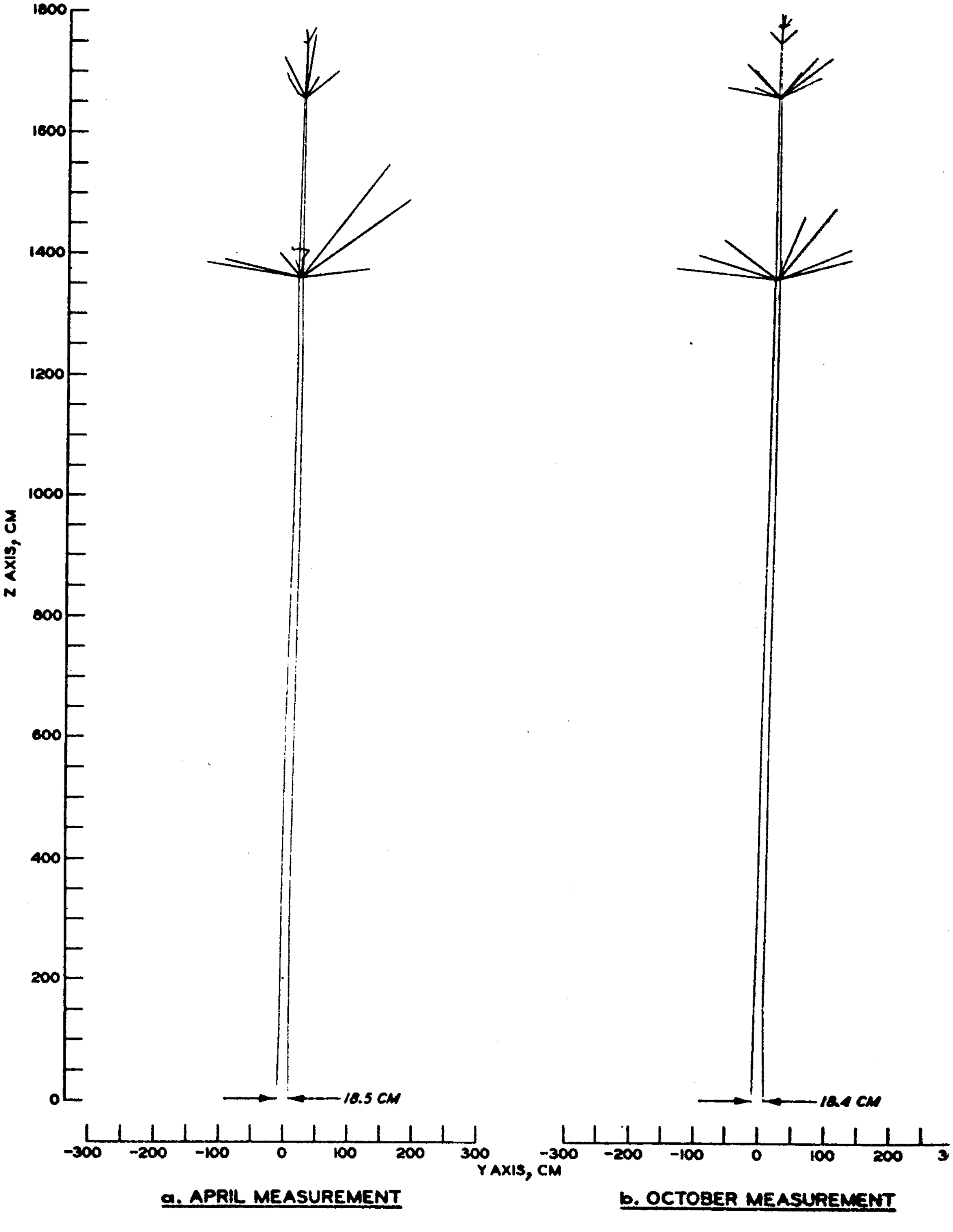

Figure 2. Graphic display of point location data from a Douglas-fir tree near Seattle, Washington, on which branching was not surveyed in detail. Bole graphed to show diameter to scale.

ing methods. Every point in the sample space is thus located with respect to any arbitrarily defined three-coordinate system. Details of the procedure are presented elsewhere (West and Allen 1971).[1]

One of the theodolites is equipped with a specially designed circular reticle for measuring branch or stem diameter, employing the principle of stadia measurement. All measured angles and reticle readings are recorded in the field on specially designed data forms, and trigonometric conversions of field data to point locations and stem or branch diameters are made by computer. Figure 2 is an example of a computer graphic of one of the trees on the Thompson site.

Description of the Sample

The Douglas-fir stand, located on the A. E. Thompson Research Area in the Cedar River watershed, lies some 64 km southeast of Seattle, Washington. The Research Area is described in detail by Cole and Gessel (1968). Measurements were obtained from a group of eight contiguous trees on each of two proximate (not contiguous) permanent research plots (designated 1 and 2 on the Research Area) within an even-aged 40-year-old plantation. Plot 1 received three applications of nitrogen as ammonium sulfate $(NH_4)_2SO_4$ at the rate of 222 kg/ha in October 1963, October 1964, and May 1970. Plot 2 was left untreated as a control.

The eight trees selected for measurement on each plot were selected first by choosing an arbitrary point within each plot, and then taking the eight trees nearest to each point as sampling trees. The only controlling criterion placed upon location of the starting point on each plot was that it should be far enough within the plot to avoid inclusion of boundary trees in the sample. Measurements on the sample trees were made in April 1970, before bud burst, and then again in October 1970, after the apparent end of the growing season.

[1] E. E. Addor and H. W. West. A technique for measuring the three-dimensional geometry of standing trees. U.S. Army Waterways Experiment Station, Vicksburg, Mississippi. Unpublished.

Data were taken to include the coordinate location and the diameter (outside bark) at the following points:

a) At the base of the tree, defined as being at the duff line or ground line, as well as could be determined. Diameters were measured with a tape.
b) Diameters at breast height (d.b.h.) 150 cm above the duff line were marked with a ribbon for subsequent remeasurement.
c) The bole at every fourth whorl where limbs were still present (diameters were calculated from reticle readings).
d) The base of the live crown, defined as the lowermost whorl at which more than 50 percent of the branches held green leaves. The location of a whorl is defined as the approximate centroid of branch emergence; diameter measurements on the bole are made just below the lowermost branch as well as just above the uppermost branch of the whorl (fig. 3). (Diameters calculated from reticle readings.)
e) At every fourth branch whorl within the live crown, or at least one branch whorl within the middle one-third of the live crown.
f) The topmost whorl in April and that same whorl plus the new topmost whorl in October.
g) The top of the leader, at the base of the terminal bud whorl.

Figure 3. Definition of branch whorl location, and location of diameter measurements at whorl.

h) Point locations and diameters were measured for various defined points on crown branches but will not be discussed here.

A total of 30 turning points (instrument set-ups) were established for the April survey and all were referenced to a common coordinate system. The same points of reference were used again in October, but no deliberate attempt was made to duplicate the surveying sequence, e.g., to site each point on the tree and to measure each diameter from the same turning point. Nonetheless, the sequence that was adopted for the first survey was approximated during the second survey, as a result of constraints within the stand. Thus the sampled points were mostly viewed from the sample angles during both surveys. Since both surveys were referenced to the same coordinate system, the reported coordinate locations of surveyed points are in theory exactly comparable, so that any difference in the reported location of a point represents a displacement of that point by wind action, growth, or survey error.

Results of Theodolite Survey

Crown Cover and Stand Density

The crown cover was essentially closed and the branching structure relatively dense. The ground area occupied by the eight sampled trees on each plot was determined in April by traversing the ground points representing the outer crown limits of the outermost trees of the group. The crown coverage so determined was 31.2 m^2 on plot 2 (unfertilized) and 44.0 m^2 on plot 1 (fertilized) representing a crown area per tree of 3.9 m^2 and 5.5 m^2, respectively, or a density of approximately 2,567 and 1,818 trees per hectare.

In this same stand, in October, 1965, Dice (1970) destructively analyzed 10 trees from a 0.0045-hectare (45 m^2) plot, which is 4.5 m^2 per tree, or approximately 2,222 trees per hectare. These values lie reasonably between our values for the unfertilized and fertilized trees. Unfortunately we are not certain how the crown boundaries of his trees relate to the boundaries of his 45 m^2 plot.

The problem of the true relation of the crown cover per tree (tree mean area) to sample plot boundaries is controversial (Greig-Smith 1964). Supposedly, tree randomness with respect to sample-plot boundaries should balance the excluded and included portions of included and excluded trees, but the true relation is apparently complicated by both plot size and plot shape. A crown-limit traverse is relatively simple with a theodolite survey and is easily converted to area by the computer. It should therefore be worthwhile to examine whether such a procedure would resolve the problem of the relation between sample plot boundary and tree crown boundary in the determination of crown cover, stand density, or tree mean area.

Patterns in Diameter Measurements

Examination of the diameter data from the theodolite survey suggests that the unfertilized trees exhibited greater increment on the upper portion of the bole than on the lower, whereas the fertilized trees showed approximately equal growth pattern throughout the length of the bole. Such patterns seem reasonable because of the difference in stand density. Similar patterns have been reported in unthinned and thinned stands of Douglas-fir surveyed with an optical dendrometer over a 2-year period (Groman and Berg 1971).

Certain sources of inaccuracies in diameter measurements with the theodolite system should be mentioned. First, diameters calculated from reticle readings are dependent upon accurate measurements of the distance. Second, interpolation errors from this source may be important when estimating small branch diameters with the reticle. Countering these disadvantages is the possibility of measuring diameter at any point on a stem or branch regardless of the direction or angle of inclination. Other instruments such as the optical dendrometer have no reticle inscripted and thus are restricted to measuring bole diameter.

Patterns in Point Displacement

Measuring changes in the physical structure of vegetation consists primarily of simply measuring the displacement of defined points over a specified time interval. Obviously, an error in determining the location of a point either at the beginning or at the end of the time interval will result in an error in the measurement of displacement.

Measurement errors may stem from a variety of sources, depending upon the methods of measurement. Since theodolite surveying is dependent upon calculation of point locations by trigonometric relations, both instruments must be precisely sighted on the spot to be located. Disparities in the assumed location of the target point will cause errors in the calculated location of the point. Horizontal disparities will cause horizontal and vertical errors according to the angle of convergence and the slope of lines-of-site, while a vertical disparity will not locate a point at all.

To reduce errors from this cause, a spotting laser (fig. 1) can be used to project a bright orange spot a few millimeters in diameter onto the tree at the selected target point. This provides a definitive target for sighting the theodolites at one given time, but it does not resolve the problem of relocating the exact point of measurement for periodic remeasurement. The spotting laser was at the Thompson Site during both the April and October surveys, but it was inoperable much of the time. Periods of its use and nonuse may account for some of the patterns in the data.

Other sources of error include the usual reading and transcription errors by instrument men and note keepers. Errors from these various sources may or may not be critical, depending upon their magnitude and frequency, and the special purpose for which the survey is being made. For the purpose of monitoring subtle changes in the vegetation structure over a brief time period, even very small errors may be important. Gross anomalies in the data may be identified and approximately corrected during data editing and preliminary analysis, but small errors regardless of source may not be distinguishable from true displacement.

For the purpose of discussion, any difference between the calculated location of a defined point from one observation to another (specifically, for the present case, from April to October), in any coordinate direction, may be defined as an "apparent displacement" of that point in that direction. It can then be defined that the apparent displacement always consists of two components: True displacement resulting from changes in the shapes of the trees, and errors resulting from inaccuracies and mistakes in instrument reading, note keeping, and calculations. Hereinafter, these latter will be referred to collectively as "survey error." The question to be resolved, then, is what proportion of apparent displacement can be attributed to each of these two components. Data from the surveyed Douglas-fir stand provide an opportunity to examine the theodolite surveying system with respect to these problems.

Figure 4 is a set of graphs of the apparent displacement in the xy (horizontal) plant of defined points at various levels on the tree boles, as measured from April to October. They are: (A) at the base of the tree, (B) at the base of the live crown, (C) at an arbitrary intracrown whorl, and (D) at the whorl that was defined as the topmost whorl in April (i.e., at the base of the April leader, three trees are omitted from the intracrown whorl data due to omissions in the survey). With few exceptions, the apparent displacement in the horizontal plane at the base of the tree is within plus or minus 3 cm, with a slight systematic bias in the positive x direction and in the negative y direction, but with the points for the unfertilized and fertilized trees reasonably well interspersed. Since trees are anchored at the base, it may be assumed that any apparent displacement of the tree axis in the horizontal plane at that level must represent a surveying error. Therefore this slight systematic error at this level on these trees may be interpreted as a horizontal error in relocating the established origin of the coordinate system. The absence of a separation in this plane at this level between the apparent displacement of the unfertilized and fertilized

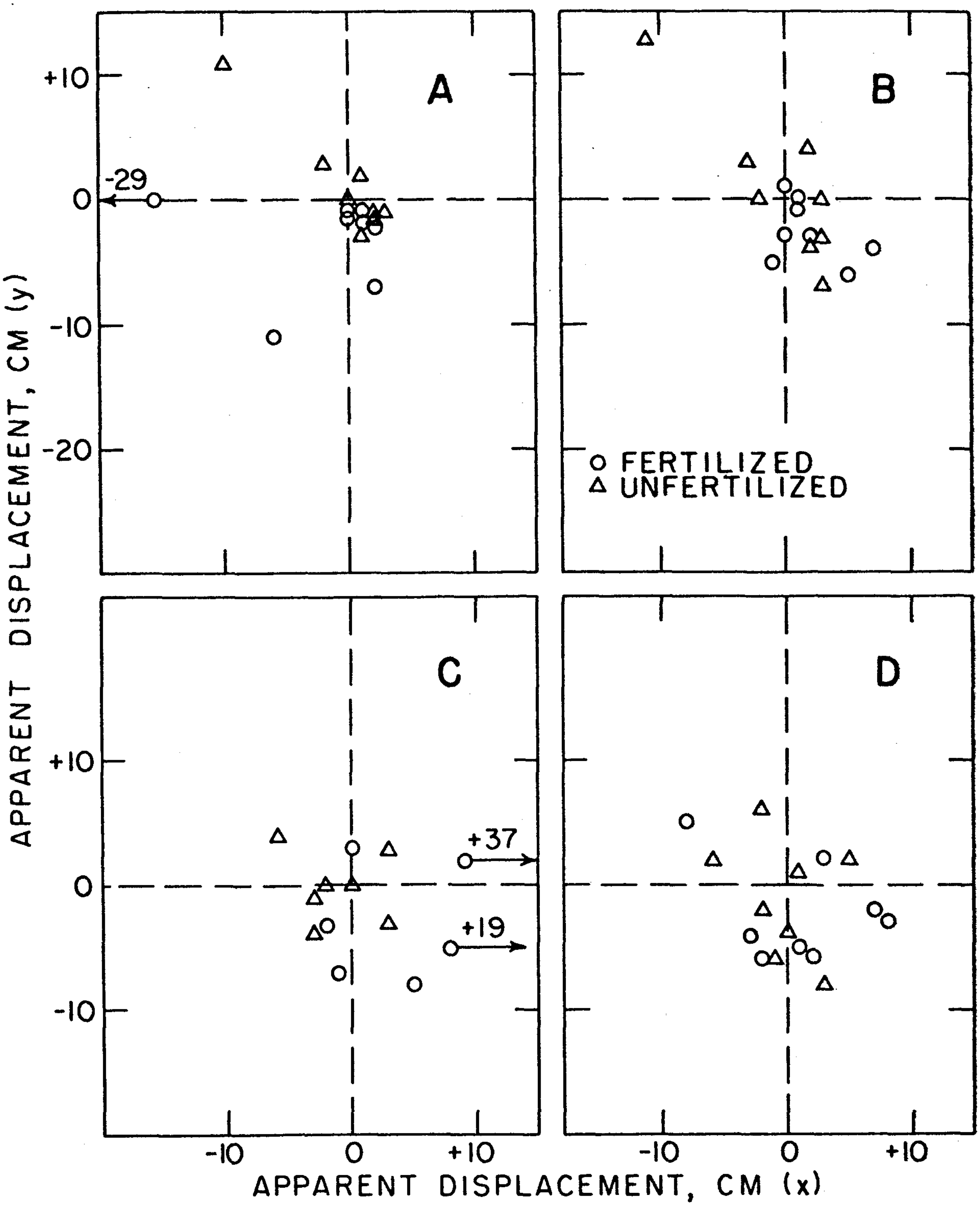

Figure 4. Apparent displacement of the tree boles in *x* and *y* (the horizontal plane) at various levels on the sampled trees, from April to October: (A) at the base of the trees, (B) at the base of the live crowns, (C) at an intracrown whorl, (D) at the base of the April leader (based on data from table 2 in West and Allen 1971).

trees indicates that the coordinate system was surveyed across the intervening distance between the two plots (about 20 m) with negligible error in this plane. If the data are adjusted for the horizontal error in relocation of the coordinate system origin, then the displacement error is quite small, and it must be conceded that remeasurement of the horizontal angles to the trees has been achieved with a fair degree of success, despite the 30 turning points used in accomplishing the survey.

Two explanations may be suggested for the increasing scatter of points in the horizontal plane with increasing height on the tree, shown on figure 4B, C, and D. First, it may be assumed that surveying errors have increased with increasing elevation of lines-of-site, or second, it may be assumed that the position of the boles are less stable in the horizontal plane at higher levels on the tree. Since point locations in the horizontal plane are calculated from horizontal angles, irrespective of angles of elevation, there is no reason to assume that surveying errors should increase in relation to elevation. It follows therefore that errors in the location of points in the horizontal plane at any elevation might be equal to, but should not exceed, the errors in location of the base of the trees in this plane. It follows in turn that the apparent horizontal displacement of points on the upper boles of these trees must be a true displacement. The pattern is consistent with what would be expected as a result of movement of the trees by wind.

Figure 5 is a set of graphs of the apparent displacement of z (the vertical plane, or elevation) for the same defined points on the bole that are shown on figure 4, respectively. These show a considerable scatter in the apparent vertical displacement at the base of the live crown, moderate scatter in apparent vertical displacement at the intracrown whorl, and again a relatively close clustering of apparent displacement at the base of the April leader.

This pattern of variation may be attributed to relative differences in the difficulty of identifying the defined points with respect to elevation. This difficulty is more or less inherent in the definition of the points; that is to say that "at or near the duff or ground line" is less definitive than is "the centroid of the branch whorl," whereas the topmost whorl (base of the leader) is the smallest and most definitive of the defined points. The differences in vertical scatter of points for the base of the live crowns and for the intracrown whorl may be attributed to errors of approximating the exact elevational location of the latter through obscuring branches and foliage. These inconsistencies of identification have important implications with regard to measurement of length relations, such as the total height of trees or the ratio of bole length to length of live crown (although, of course, the significance of the implication is determined by the magnitude of the dimensions and the special purpose for which the relations are being measured).

It was observed above that the apparent displacement of defined points on the unfertilized and the fertilized trees were reasonably well interspersed with respect to the horizontal plane. With respect to elevation, however, the data exhibit systematic tendencies that require explanation. Specifically, figure 5B shows a seemingly strong tendency toward a positive apparent displacement of about 6 or 7 cm for the base of live crowns on the fertilized trees, while the apparent displacement of this point on the unfertilized trees appears to be randomly dispersed about zero. A possible explanation is that a vertical error was committed in extending the coordinate system across the distance (approximately 20 m) between the two groups of trees. However, if this were the case, then the same apparent vertical displacement must occur at all other levels on the fertilized trees; if it does not, then its absence from other levels must be accounted for. The data for the intracrown whorl (fig. 5C), though somewhat more scattered than the data for the base of live crown, do indeed suggest a similar disparity between central tendencies for the two groups of trees, but a similar disparity is not obvious at the base of the trees (fig. 5A), nor at the base of the April leaders (fig. 5D). It may be that for the base of the tree, the disparity is simply obscured by the scatter of the

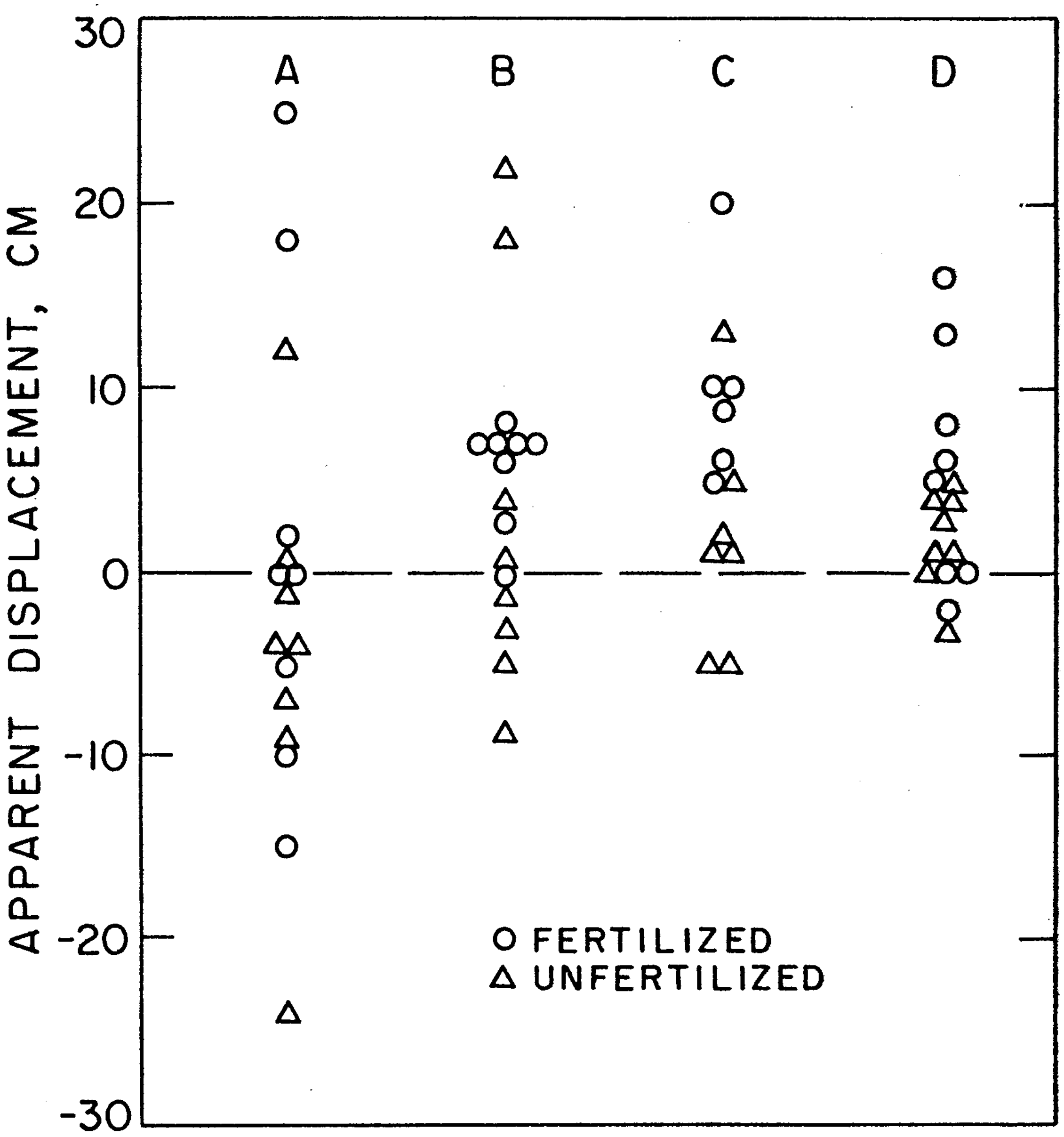

Figure 5. Apparent displacement of points on the tree boles in x and y as a function of z (elevation), from April to October: (A) at the base of the trees, (B) at the base of the live crowns, (C) at an intracrown whorl, (D) at the base of the April leader (based on data from table 2 in West and Allen 1971).

data; there is no obvious explanation for its absence at the base of the April leader.

Conclusions

The preliminary survey of Douglas-fir trees at the Thompson Site suggests that theodolite surveying is adaptable to the purpose of detecting and monitoring subtle patterns of change in vegetation structures. In terms of quantity and quality of data obtained for the energy expended, this procedure appears to be commensurate with any other known tree measurement system, and it offers advantages not offered by any other system. First, because the location of every point in the sample is determined relative to an arbitrary point defined as the origin of the coordinate system, the apparent displacement of any point on the tree is independent of the apparent location of any other point on the tree. Second, displacement of points in any direction can be measured with this procedure, such as, for example, the tips of branches radially disposed about the stem and growing at various angles from the vertical. Finally, and of considerable importance, this system is entirely nondestructive and is therefore well suited to continued monitoring of growth trends over extended time periods.

Theoretically, the precision of the technique is within millimeters, since it is basically the same as is used for precision engineering surveying. There are, however, a few practical limitations on the attainable precision. Following are a few observations about particular problems.

A possible solution to the problem of target point identification would be to climb the trees prior to the initial survey and afix permanent sighting targets at points of interest. Also, a network of similarly small definitive targets could be established throughout the sample area for use as permanent reference points, one of which could be used to define the origin of the coordinate system. A series of carefully controlled experiments should be designed specifically to determine the effects of operator error on the limits of attainable precision under different kinds of working conditions.

Dense crown branches and foliage may place constraints on the usefulness or convenience of this method in some kinds of vegetation.

When precision is required, surveying should be avoided during periods of adverse weather conditions. Tarpaulins can be suspended over the instruments so that work may be carried on during rain or snow, but these conditions also affect visibility within the forest. Winds that are strong enough to cause movement of the trees will obviously increase the probability of meaningless apparent displacements, and should be avoided.

As of this writing, the system has been used exclusively for the dimensioning of trees. The principles upon which it is based, however, are universally applicable mathematical relations. Therefore the technique should be eminently suited to the study of a variety of ecological problems involving relations that can be described in a three-coordinate system. These might include, for example, the structure of bird rookeries, the spatial arrangement of epiphyte or parasite plants, or flower and fruit distributions.

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