COMPARISON OF TECHNIQUES TO MEASURE TREE INTERNODE LENGTHS

J. A. Turner

Report No. 18 November 1995

FOREST & FARM PLANTATION MANAGEMENT COOPERATIVE

EXECUTIVE SUMMARY

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To obtain reliable data for the study of branch habit in genetically improved *Pinus radiata* a method of internode length measurement is needed which is accurate, precise, rapid and safe. Four techniques of internode length measurement were analysed;

- tree climbing;
- height pole;
- Forestor vertex;
- whorl counts.

The above four methods were compared in terms of their ability to estimate mean internode length (MIL) and mean internode index (MIX) for various sections of the tree stem up to 12 m. Each method was analysed for bias and variability in their estimates of MIL and MIX. The climbing method was assumed to be the most accurate, so the other three methods were compared with this technique. The methods were also compared in terms of time taken to carry out measurements, and level of safety.

The results of this study show that while the tree climbing method is likely to be the most accurate means of estimating MIL on a standing tree it has drawbacks under the conditions in which this study was carried out due to lack of safety, and the time consuming nature of the method. The height pole method is the most appropriate means of estimation of MIL and MIX in terms of meeting the accuracy, ease of use and safety requirements. The height pole method also tends to have a low variability in MIL and MIX estimates from the actual measures. The whorl count method is not an appropriate means of rapidly appraising MIL in improved breeds due to the variability in whorl depth of improved *P. radiata*. The whorl count method must also be used in conjunction with a height pole or vertex to identify the top and base of the stem section being measured. The vertex method, while being a rapid measurement technique, has large bias and variability in its estimates of MIL due to difficulties in identifying whorl position using the instrument.

INTRODUCTION

The genetic gain modifiers study (Turner, *et al*, 1995) aims to develop genetic gain modifiers related to breeding values[1]. These genetic gain modifiers for mean internode length (MIL), mean internode index (MIX), stem straightness, malformation, and density are to be included in STANDPAK. In order to develop the appropriate genetic modifiers quantitative measures need to be made of branch habit, stem straightness, malformation and wood density for numerous progeny of the parents in the Genetics and Tree Improvement (GTI) breeding programme. The relationship established between the subjective GTI scores and quantitative measurement of log quality factors, can be used to develop modifiers in STANDPAK for all parents in the GTI breeding programme.

To obtain reliable data for the study of branch habit in genetically improved material a method of measurement is needed which is accurate, precise, rapid and safe. Good levels of accuracy and precision are needed to measure the subtle differences in branching habit apparent in improved breeds of *Pinus radiata*. The measurement technique must be rapid as a large number of trees are needed to provide a precise estimate of MIL and MIX. Being able to carry out rapid measurement will reduce the cost of measuring a large sample set. Speed of measurement still needs to be weighed against achieving a certain level of accuracy. Safety is an important requirement under the Occupational Safety and Health Act (1991).

Two basic methods of tree internode length measurement have been used in the past:

- climbing (Woods, 1988; Woods and Carson, 1988; Carson and Inglis, 1988);
- height pole (Woods, 1988; Woods and Carson, 1988; Turner, 1994).

Another method suggested for the rapid appraisal of MIL and MIX for STANDPAK input is:

- whorl counts (Woods, 1988; Woods and Carson, 1988).

A method of internode length measurement which has recently become possible due to technological advances is the:

- Forestor Vertex (Appendix I).

This study compares the height pole, whorl count and vertex methods of internode length measurement with the tree climbing method in terms of their ability to estimate

[1] the breeding value judges the value of an individual in terms of the mean value of its progeny (Falconer, 1989).

tree MIL and MIX. The methods were compared for bias and level of variability in their estimates. A comparison of the time and safety factors involved with each method was also made.

METHOD

SITE/ PLOT SELECTION

Plots 6/2 and 6/4 in the Kaingaroa 1975 "850" polycross were used for tree measurement. A total of 31 trees which are from parents used in the genetic gain modifiers study (Turner, *et al*, in prep) were selected for measurement covering a range of MIL from approximately 0.20 m to 1.20 m. This enabled a comparison of the ease of measurement and accuracy of the 3 methods against the climbing method for both multinodal and "uninodal" material.

MEASUREMENT TECHNIQUES

The four methods of internode length measurement are:

- tree climbing;
- height pole;
- Forestor Vertex;
- whorl counts.

For each of the first three methods the following measurement technique was used. Each branch whorl was measured between a 0.2 m stump height to the base of the first whorl above 12 m. A stem cone whorl was measured as the end of an internode, even if the stem cone whorl had no branches associated with it. Where two or more branch whorls occurred close together and there was no discernible internode, the whorls were counted as one. This occurs when branches from the top whorl grow from the region in which the lower branch whorl occurs in the stem (Fig. 1). For the tree climbing and height pole methods the base and top of each whorl were measured to ± 0.05 m (Fig. 2). Measurements were made to ±0.05 m as this was a realistic level of accuracy of measurement while still ensuring the subtle differences in branching habit between families could be identified. The level of data display of the Forestor Vertex only permitted measurements to ±0.1 m. Each tree was measured by the same operator using each of the four methods. The same side of the tree was measured when each method was used.

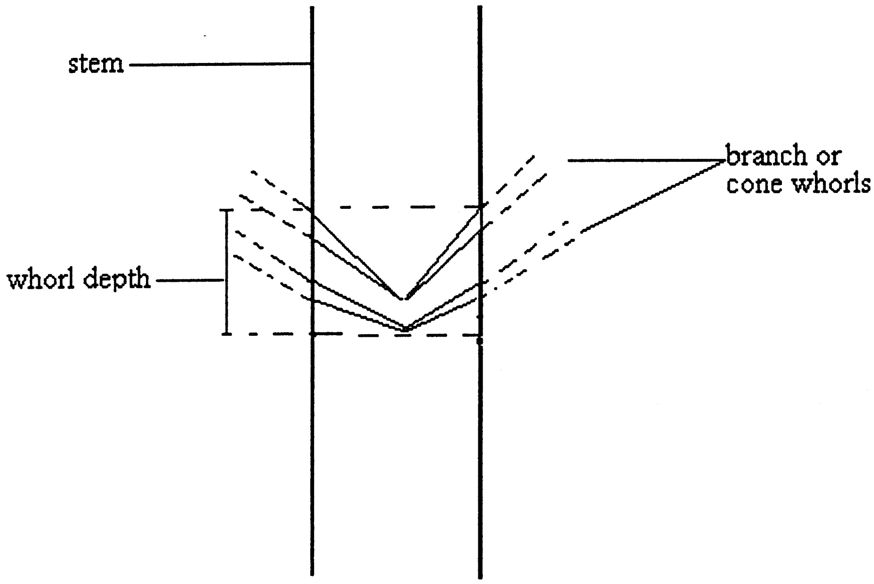

Figure 1. Whorl depth for whorls occurring close together. Source: Woods (1988).

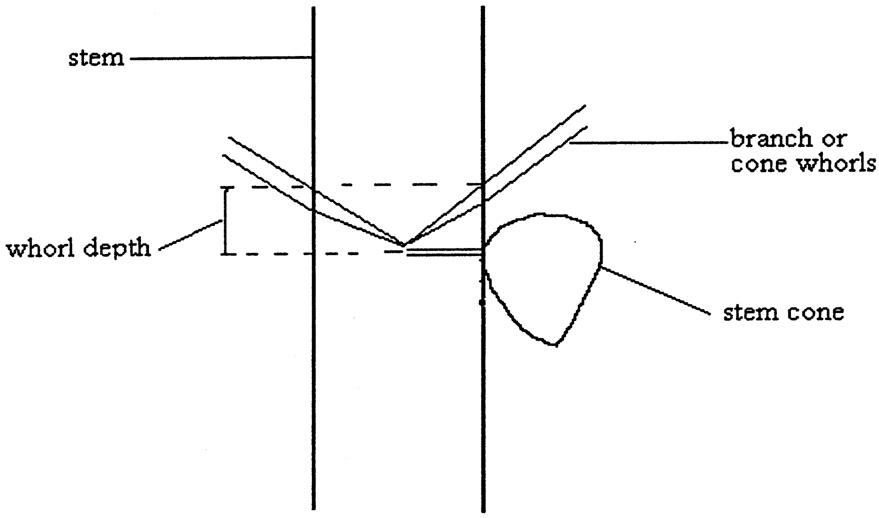

Figure 2. Whorl depth illustrated. Source: Woods and Carson (1988).

Tree Climbing

The tree climbing method involved a person directly climbing each tree with a tape measure (Carson and Inglis, 1988). Most of the trees measured were pruned to 6 m so a ladder was needed to reach the first branch. Above the pruned section the branches were climbed.

Height Pole

The height pole method (Woods, 1988; Woods and Carson, 1988; Turner, 1994) involved placing the height pole parallel to and as close to the stem as possible on the uphill side of the tree, allowing for a 0.2 m stump (Fig. 3).

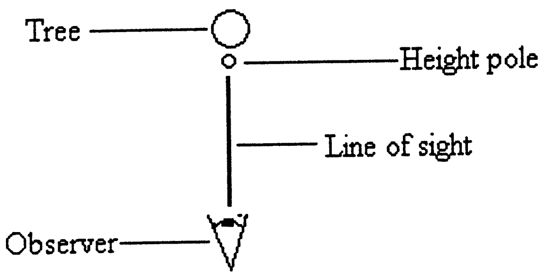

Fig. 3. Plan view of height pole, observer and tree. Source: Woods (1988).

Forestor Vertex

The Forestor Vertex (Appendix I) hypsometer consists of two units - the hypsometer unit and the transponder. The transponder emits an ultra-sonic signal which is used by the hypsometer to measure the distance from the observer to the tree and calculate height based on two angles and the distance. The height to the base and top of each whorl was then measured.

Whorl Count

The whorl count method (Woods, 1988; Woods and Carson, 1988) involves counting the number of whorls over the section of stem being studied, estimating tree or stand mean whorl depth and deciding whether or not branch whorls coincide with the ends of the log. The whorl depth was estimated at 0.2 m for the whole stand based on measures of whorl depth made by Inglis and Cleland (1982), Woods and Carson (1988); Tombleson, Carson and Inglis (1988); Grace and Inglis (1990); Knowles and

Kimberley (1992). The number of whorls were counted from visual appraisal. The top and base of the branched stem section was that measured with the height pole.

From these parameters the MIL was calculated using the following formulae (Woods, 1988; Woods and Carson, 1988):

$$\mathbf{MIL} = \frac{\mathbf{l - (n * d)}}{\mathbf{n + (I - 1)}}$$

where **MIL** is mean internode length for the log length measured;

l is the length of stem or log being measured;

n is the number of branch and/ or stem cone whorls per length of stem or log being measured;

d whorl depth (estimated);

I is the number of times for each stem or log that the end of the indicated "log" does not coincide with a branch or stem cone whorl, ie., 0, 1, or 2.

An important consideration in the estimate of MIL from whorl counts, particularly when measuring improved breeds of *P. radiata*, is the sensitivity of the calculated MIL to errors in the estimate of whorl depth. A sensitivity analysis of MIL to changes in estimates of whorl depth (Woods, 1988) indicates that for longer internode material errors are small, however, for more multinodal trees a larger error in MIL estimation can occur. For trees with a MIL of 0.28 m, a ±0.01 m error in estimating whorl depth will result in errors up to 3.6%. This is particularly important to consider when measuring trees in Woodhill forest where "850[2]" seed orchard material has an average MIL of 0.35 m in the first 5.5 m log (Carson and Inglis, 1988).

SPEED OF MEASUREMENT

The number of trees measured in an hour was estimated to gain an indication of the relative speed of each method. The estimate of height pole measurement speed was based on previous work using the height pole carried out by Turner (1994). The estimate of the speed of measurement of the vertex was based on the number of trees the Forestry Corporation of New Zealand had achieved measuring a similar section of the tree stem for MIL. The data gathered from these sources is indicative only of the

[2]The number "850" is a prefix number denoting a particular series of clone. The first digit in the clonal series number refers to the regional origin of the clone (8 signifies collections carried out by FRI, not necessarily within one conservancy). The second two digits refer to the year of selection, in this, case 1950 (Vincent & Dunstan, 1989).

likely speed of each method, and so provides a ranking rather than an absolute measure of the speed of each method.

DATA ANALYSIS

The three methods, height pole, vertex and whorl count were compared with the climbing method in terms of their ability to estimate MIL and MIX. The climbing method estimates of MIL and MIX themselves have a small measurement error in them. By comparing the three methods with climbing through regression analysis the error in climbing estimates of MIL and MIX will result in trend lines having a slight positive slope (Tennent, 1983). When interpreting the regression analysis contained in this report it is, therefore, important to allow for the expected slightly positive slope of trend lines.

Several individual tree comparisons were made as an initial exploratory analysis to compare how reliably each of the methods measures whorl depth and whorl occurrence. The number of trees with the same number of whorls measured by each method indicate whether a measurement technique is over or underestimating whorl occurrence compared with the climbing method. Average whorl depth and height to the base of the whorl were calculated for trees for which the climbing measure of the number of whorls was the same as for the height pole or vertex, to establish if any methods consistently over or underestimate whorl position and/ or whorl depth.

Further data analysis was undertaken with a series of graphical representations of trends. A plot of MIL for the 3 methods against MIL for the climbing method was produced with the simple linear regression trends for the 3 methods. The Y = X line (45°) was also plotted, ie. the MIL estimated by tree climbing. This enabled comparison of levels of over and under-estimation at various MILs for the different methods.

The level of bias between the 4 methods was tested by observing if the regression lines for each of the 3 methods' had a slope of 1 and an intercept of 0 at the 95% confidence level. This analysis was based on the graphical analysis described above. This tests how similar the 3 methods are to the climbing method across the range of calculated MILs.

A plot of differences in MIL (climbing MIL minus estimated MIL) against climbing MIL was produced with trend lines to indicate levels of MIL at which the 3 methods over or underestimate actual MIL. An analysis of variance was calculated to determine whether a method had a significant trend line and was, therefore, significantly different in its estimate of MIL from the climbing method's estimate.

The 4 methods were also compared by analysing the calculated difference in estimates (residuals) between each of the 3 methods and the climbing method. These residual values were analysed for each of the methods to test if their means differed significantly from 0. The level of variability of the estimates for each of the methods was compared in terms of their residual standard deviation. Plots of the residual values for each method against estimated MIL were made to check for trends in the level of variation for different estimates of MIL.

The analyses were also performed to compare mean internode index (MIX) estimates between the 4 methods. MIX was calculated from climbing, height pole and vertex data by:

$$\mathbf{MIX} = \frac{\textbf{sum of internode lengths} \geq \mathbf{0.6\ m}}{\textbf{log length}}$$

The internode index was calculated from 6.3 m to 11.8 m to avoid the pruned section of the stem. This gave a log length of 5.5 m. Three trees had a pruned height of 6.9 m, however the estimate of MIX for these trees would be reasonably reliable because they all are highly uninodal. For the whorl count method, MIX was calculated using the regression equation derived by Woods (1988) and Woods and Carson (1988);

$$\mathbf{MIX = -0.0731 + 0.8904 * MIL}$$

A comparison of how the climbing, height pole and vertex methods measure internode length up the stem was also made. This analysis involved a plot of mean difference in internode length for the height pole and vertex compared with climbing, by 1 m height classes up the stem. A statistical comparison was made by fitting a regression line to the residuals against stem height and checking if the slope is 0 at the 95% level.

RESULTS AND DISCUSSION

INDIVIDUAL TREE COMPARISONS

The comparisons of numbers of whorls measured by each method (Tables 1 and 2) indicate the height pole tends to measure the number of whorls more consistently than the vertex. If there is a difference in the number of whorls measured between the two techniques and the climbing method then they tend to measure fewer whorls than the climbing method.

	NUMBER OF TREES
All 3 methods the same	3
Pole and climbing the same	13
Vertex and climbing the same	6
Pole and vertex the same	4
All different	5

Table 1: Comparison of number of trees which had the same number of whorls measured by each of the methods used to assess internode length.

		PERCENTAGE
Height pole	same number of whorls	52
	more whorls measured by climbing	29
	more whorls measured by pole	19
Vertex	same number of whorls	29
	more whorls measured by climbing	42
	more whorls measured by vertex	29

Table 2: Percentage of trees for which the height pole or vertex measured more than, less than or the same number of whorls as the climbing method.

There are three reasons why the techniques of internode length measurement differ in their estimates of the number of whorls on the stem section measured, two whorls are measured as one because there is no discernible internode, a whorl is not measured or a whorl which occurs above 12 m is measured as occurring below 12 m. Underestimation of whorl number by the height pole is due to both counting two whorls as one and missing whorls (Table 3). The main reason for overestimation of whorl number measured by the height pole (Table 4) is due to missing whorls. Tables 5 and 6 show that the vertex commonly misses whorls when the method underestimates whorl number and will add whorls where the method overestimates whorl number.

LESS WHORLS MEASURED BY THE HEIGHT POLE	
Cause	**Percentage Occurrence**
Two whorls measured as one	40
Whorl missed by height pole	47
12 m limit	13

Table 3: Percentage occurrence of the three causes of underestimation of the number of whorls as measured by the height pole compared with the climbing method.

MORE WHORLS MEASURED BY THE HEIGHT POLE	
Cause	**Percentage Occurrence**
Two whorls measured as one	0
Whorl missed by climbing	66
12 m limit	44

Table 4: Percentage occurrence of the three causes of overestimation of the number of whorls as measured by the height pole compared with the climbing method.

LESS WHORLS MEASURED BY THE VERTEX	
Cause	**Percentage Occurrence**
Two whorls measured as one	27
Whorl missed by vertex	64
12 m limit	9

Table 5: Percentage occurrence of the three causes of underestimation of the number of whorls as measured by the vertex compared with the climbing method.

MORE WHORLS MEASURED BY THE VERTEX	
Cause	**Percentage Occurrence**
Two whorls measured as one	11
Whorl missed by climbing	72
12 m limit	17

Table 6: Percentage occurrence of the three causes of overestimation of the number of whorls as measured by the vertex compared with the climbing method.

Both the height pole and the vertex rarely measure the whorl depth accurately as shown by the percentage of cases in which each of the methods over or underestimates whorl depth on trees for which the same number of whorls as measured by the climbing method were measured by the height pole or vertex(Table 7). The vertex tends to underestimate whorl depth. The height pole shows no particular propensity to overestimation or underestimation.

		PERCENTAGE
Height pole	same whorl depth	12
	larger whorl depth	44
	smaller whorl depth	44
Vertex	same whorl depth	11
	larger whorl depth	33
	smaller whorl depth	56

Table 7: Percentage of trees for which the height pole or vertex measured larger, smaller, or the same whorl depth as the climbing method for trees for which the methods measured the same number of whorls as the climbing method.

The average height to the base of the whorl and the average whorl depth for each tree in which the same number of whorls were measured by the height pole and climbing methods (Table 8) shows that the height pole does not significantly underestimate or overestimate whorl depth, or height to the base of the whorl compared with the climbing method.

	CLIMBING	STD ERR	HEIGHT POLE	STD ERR
Average whorl depth	0.18	0.009	0.19	0.011
Average height to the base of the whorl	9.42	0.153	9.10	0.126

Table 8: Average height to base of whorls and average whorl depth for the climbing and height pole methods for trees which the two methods measured the same number of whorls.

The average height to the base of the whorl and the average whorl depth for each tree in which the same number of whorls were measured by the vertex and climbing methods (Table 9) indicates that the vertex does not significantly underestimate or overestimate whorl depth or height to the base of the whorl compared with the climbing method.

	CLIMBING	STD ERR	VERTEX	STD ERR
Average whorl depth	0.17	0.01	0.17	0.01
Average height to the base of the whorl	9.61	0.21	9.19	0.26

Table 9: Average height to base of whorls and average whorl depth for the climbing and vertex methods for trees which the two methods measured the same number of whorls.

For trees for which the same number of whorls were measured by climbing and the vertex or height pole, both the height pole tends to overestimate the height to the base of the whorl and the vertex tends to underestimate the height to the base of the whorl (Figure 4 and Table 10). The trends in estimates of the height to whorl base for both the height pole and the vertex are not significant, indicating there is no tendency to increasingly over or underestimate height to whorl base further up the stem. There appears to be a greater variance in the estimates of height to whorl base when whorls are measured above 6 m.

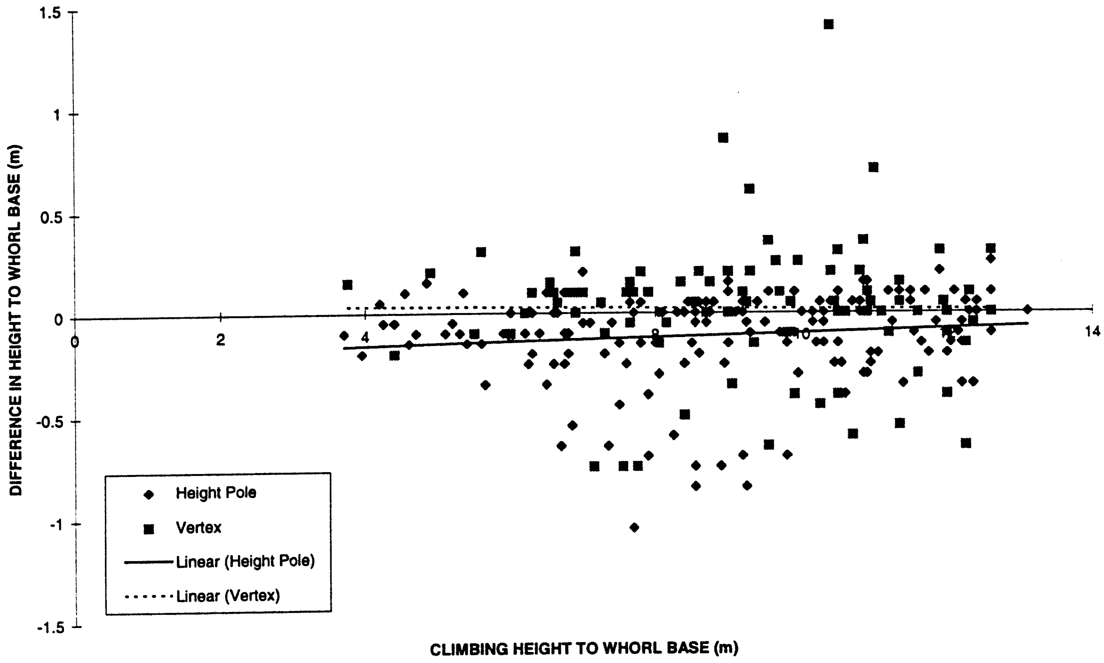

Fig. 4: Difference in height to whorl base estimated by the height pole and vertex methods compared with the climbing method for trees measured with the same number of whorls as measured by the climbing method.

METHOD	SLOPE	LOWER 95%	UPPER 95%	P-VALUE	
Height pole	0.010	-0.01	0.03	0.20	not significant
Vertex	-0.002	-0.04	0.03	0.89	not significant

Table 10: Estimated slope and 95% confidence interval for the slope estimate for the difference in height to whorl base against climbing estimate of height to whorl base. The P-value is the probability that the slope of the trend line is zero.

A comparison of the height pole and vertex estimates of tree mean whorl depth (Figure 5 and Table 11) for trees for which the same number of whorls were measured by climbing and the height pole or vertex, indicate both methods tend to significantly overestimate whorl depth for trees with smaller whorls and underestimate whorl depth for trees with larger whorl depths. A component of this trend will be due to the error in whorl depth estimate made by the climbing method.

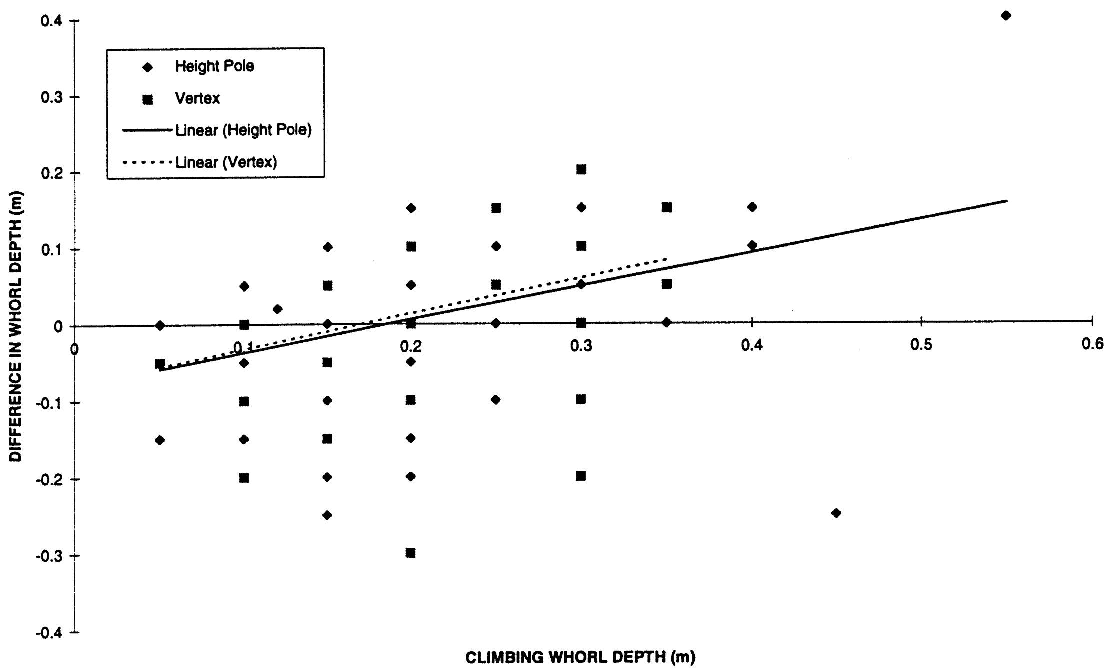

Fig 5: Comparison of whorl depth estimated by the vertex and height pole methods compared with the climbing method for trees for which the same number of whorls were measured.

METHOD	SLOPE	LOWER 95%	UPPER 95%	P-VALUE	
Height pole	0.27	0.12	0.41	0.001	significant
Vertex	0.46	0.17	0.75	0.002	significant

Table 11: Estimated slope and 95% confidence interval for the slope estimate. The P-value is the probability that the slope of the trend line is zero.

INTERNODE LENGTH ESTIMATES

MEAN INTERNODE LENGTH

The plot of the 3 measurement methods' estimations of MIL against the climbing measurement of MIL is shown in figure 6.

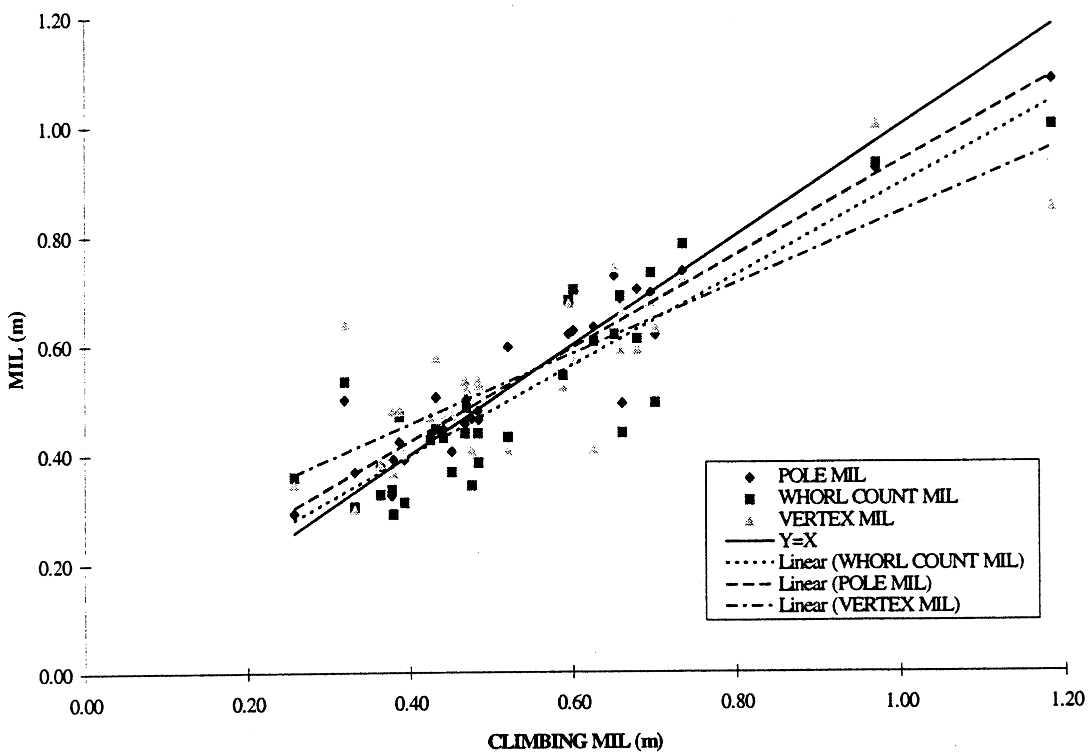

Fig. 6. Plot comparison of whorl count, height pole and vertex estimates of tree MIL against the tree climbing estimate of MIL. The Y=X line indicates the estimate of MIL made by tree climbing. The "linear" lines have been fitted using simple linear regression.

Estimates of MIL from the height pole method are closest to those made by tree climbing. All 3 methods tend to over-estimate MIL for shorter MIL and under-estimate for longer MIL. This trend is likely to be largely due to the error in MIL estimate made by the climbing method. The differences in measures of MIL arise from three components of internode length measurement. The first is the identification of "what is a whorl". This is influenced by the observers ability to distinguish whorls close together and whorls with 1 or 2 branches in one quadrant of the stem. The climbing method is the best method for enabling the measurer to identify whorls with a low number of branches and to identify whorls which may be close enough together that they should be counted as one. The second component of internode length measurement is the accuracy of each of the measurement apparatus. All methods of internode length measurement have similar levels of accuracy. The vertex and height pole though may suffer from errors due to parallax when measuring internode lengths higher on the stem. The third component of internode length measurement is the precision of the apparatus. The height pole and tape, can measure height to ±0.05 m. The vertex gives heights to ±0.1 m.

The regression coefficients and 95% confidence intervals (CI) for intercept and slope for the 3 methods' estimates of MIL (Table 12) show a significant difference between the regression lines for the vertex and the height pole, and that for tree climbing. At the 95% level the whorl count method regression line is not significantly different to the climbing method. The vertex MIL estimate associated with the highest climbing MIL estimate (Fig. 6) appears to be a contributor to the vertex's large difference in regression line compared with climbing. The point, however, while being a high influence point is not a high leverage point due to its low residual value.

METHOD		REGRESSION COEFFICIENTS	LOWER CI	UPPER CI
Whorl count	**intercept**	0.06901	-0.02856	0.16658
	slope	0.82323	0.65320	0.99325
Vertex	**intercept**	0.19817	0.09870	0.29764
	slope	0.64274	0.46941	0.81608
Height pole	**intercept**	0.08437	0.02390	0.14484
	slope	0.84997	0.74460	0.95533

Table 12. Regression coefficients and 95% confidence intervals (CI) for intercept and slope for each measurement methods' MIL estimates.

The plot of residual MIL (climbing MIL minus estimated MIL) against climbing MIL (Figure 7) and the results of the analysis of variance (Table 13) further elaborate the results of the regression analysis discussed previously. All three methods tend to overestimate MIL at lower levels of MIL and underestimate MIL at higher levels of MIL. There is a significant trend in residual MIL against climbing MIL for the height pole and vertex methods which indicate these methods are significantly biased in their estimates of MIL. A component of the error in the trend will be due to the error in MIL estimate made by the climbing method.

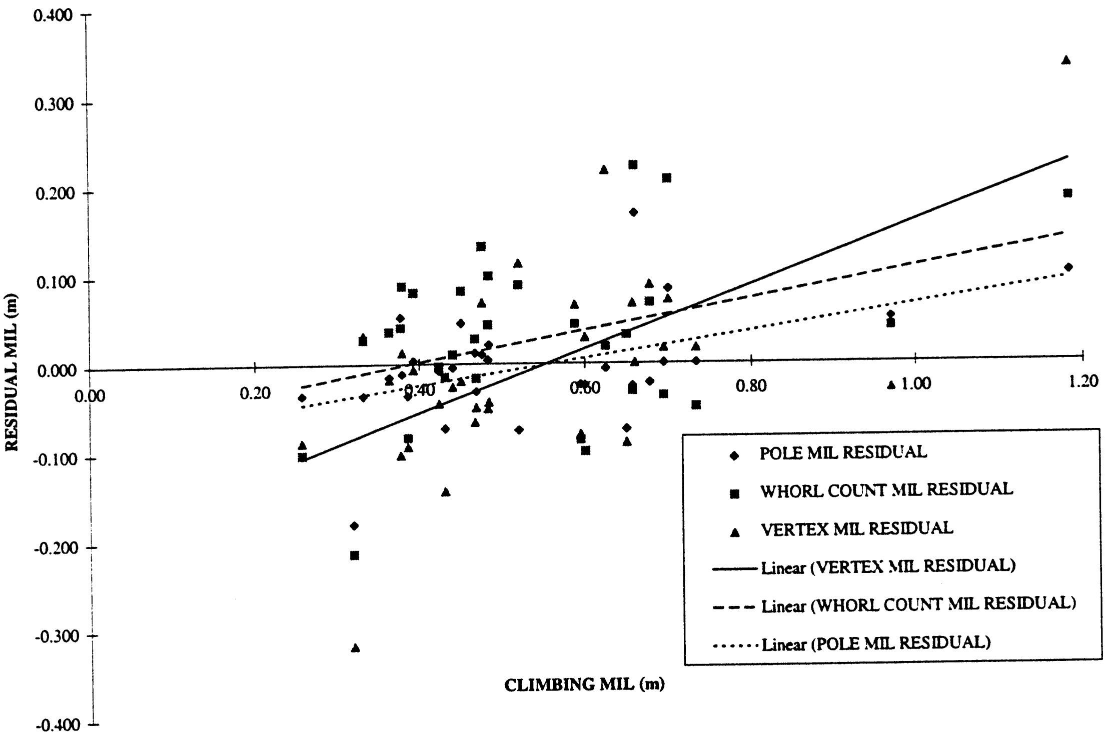

Fig. 7: Residual MIL (climbing MIL - estimated MIL) plotted against climbing MIL for each of the three methods. The trend lines were fitted using simple linear regression.

METHOD	*P* - VALUE	
Height pole	0.006836	significant
Whorl count	0.042	not significant
Vertex	0.0002	significant

Table 13: Significance of simple linear regression trend line of residual MIL against climbing MIL.

Table 14 shows the means and results of testing the null hypothesis mean = 0 for the mean difference in the 3 methods compared with the climbing method. These results indicate the whorl count mean difference is significantly different from 0 at the 5% level, so this method tends to underestimate MIL.

METHOD	MEAN	PR > 0	
Whorl count	0.0273	0.0205	r
Vertex	0.0069	0.5476	a
Height pole	-0.0012	0.9177	a

Table 14: Means and associated probabilities for each measurement method's differences in MIL from the MIL estimated by the climbing method. The probabilities relate to the null hypothesis that the mean = 0. The final column indicates whether the null hypothesis is accepted or rejected at the 95% level.

Table 15 shows the residual standard deviation for each of the 3 methods. These results indicate the height pole has the lowest variability in differences, giving a more precise estimate of MIL.

METHOD	STANDARD DEVIATION
Height pole	0.0611
Whorl count	0.0933
Vertex	0.1123

Table 15: Residual standard deviations for each of the 3 methods. The residual values are based on the difference between the height pole, whorl count and vertex methods, and the climbing method estimates of MIL.

The plots of residual values against estimated MIL for each of the 3 methods are given in Appendix II. These plots indicate the level of difference in MIL estimates between each of the 3 methods and the climbing method does not change for different levels of MIL. This means the level of difference in MIL estimates does not vary with estimated MIL.

MEAN INTERNODE INDEX

The plot of MIX estimates for each of the 3 measurement methods' against the climbing measurement of MIX is shown in figure 8.

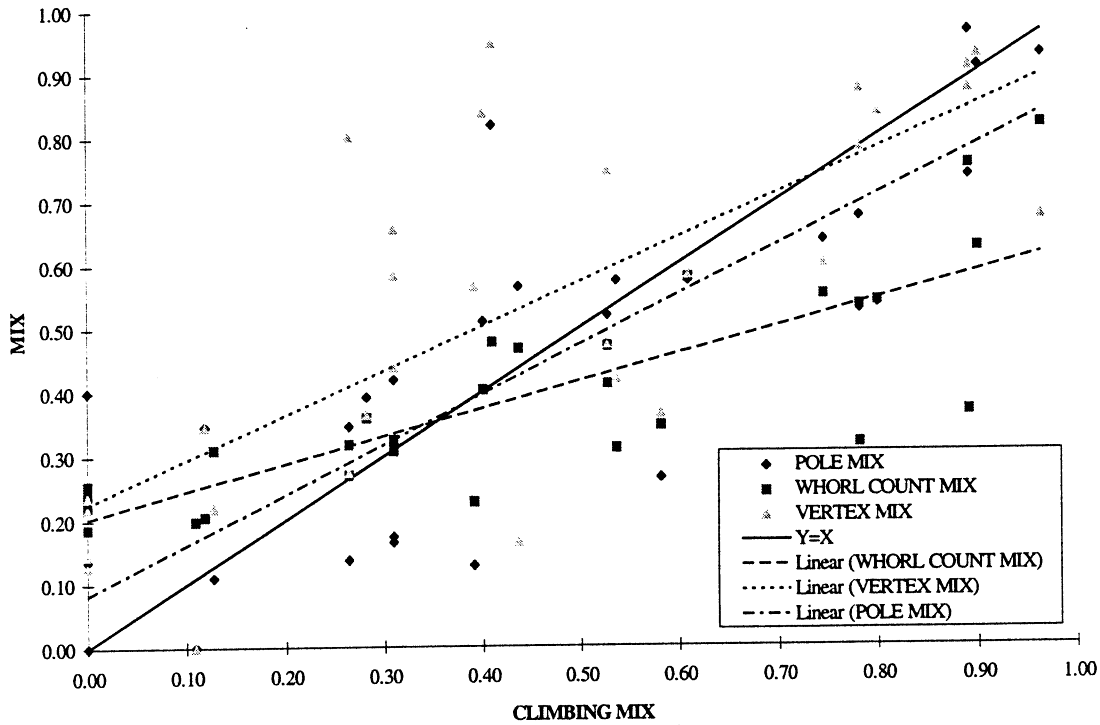

Fig. 8. Plot comparison of whorl count, height pole and vertex estimates of tree MIX against the tree climbing estimate of MIX. The Y=X line indicates the ideal estimate of MIX. The "linear" lines have been fitted using simple linear regression.

A component of the error in the trend lines for whorl count and height pole estimates of MIX is likely to be due to the error in MIX estimate made by the climbing method. The estimation of MIX is particularly sensitive to how well whorls can be identified by a method and by the accuracy of a method. If there are a large number of internode lengths which are close to 0.6 m in length the estimate of MIX will become more sensitive to the accuracy of the measurement apparatus. The height pole method appears to estimate MIX most closely to that estimated by tree climbing. The vertex gives a close estimate of MIX compared with climbing at the higher levels of MIX.

The regression coefficients and 95% confidence intervals (CI) for intercept and slope for the 3 methods' estimates of MIX (Table 16) shows a significant difference between the regression lines for the vertex, height pole and whorl count, and that for tree climbing. The height pole regression line is the most similar to the climbing estimates of MIX. The greater accuracy of height pole measurement of MIX compared with that for MIL may result from this method being more accurate at measuring the length of internodes over 0.6 m. The whorl count regression estimate of MIX is significantly different from that of climbing. This difference could be reduced by further developing the MIL, MIX relationships.

METHOD		REGRESSION COEFFICIENTS	LOWER CI	UPPER CI
Whorl count	**intercept**	0.20204	0.14125	0.26282
	slope	0.42783	0.31185	0.54382
Vertex	**intercept**	0.22475	0.10446	0.34503
	slope	0.69473	0.46522	0.92425
Height pole	**intercept**	0.08313	-0.01921	0.18548
	slope	0.78171	0.58643	0.97699

Table 16. Regression coefficients and 95% confidence intervals (CI) for intercept and slope for each measurement methods' MIX estimates.

The plot of residual MIX against climbing MIX (Figure 8) and the results of the analysis of variance (Table 17) further elaborate the results of the regression analysis discussed previously. All three methods tend to overestimate MIX at lower levels of MIX and underestimate MIX at higher levels of MIX. There is a significant trend in residual MIX against climbing MIX for the whorl count method which indicates this method is significantly biased in its estimate of MIX. This significant trend arises partly from the error in MIX estimate made by the climbing method.

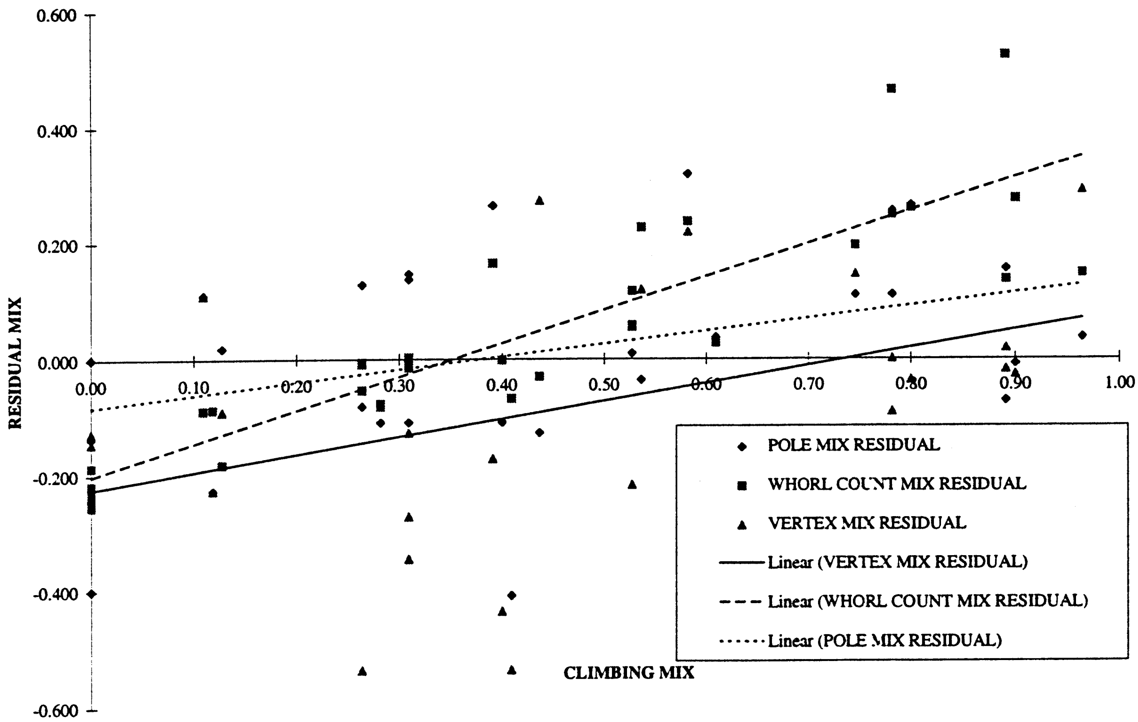

Fig. 9: Residual MIX (climbing MIX - estimated MIX) plotted against climbing MIX for each of the three methods. The trend lines were fitted using simple linear regression.

METHOD	*P* - VALUE	
Height pole	0.029734	not significant
Whorl count	0.00001	significant
Vertex	0.010908	not significant

Table 17: Significance of simple linear regression trend line of residual MIX against climbing MIX.

Table 18 shows the least square means and results of testing the null hypothesis mean = 0 for the mean difference in each of the 3 methods compared with the climbing method. These results indicate the vertex mean difference is significantly different from 0 at the 95% level, which shows this method tends to overestimate MIX.

METHOD	MEAN	PR > 0	
Height pole	0.0100	0.7293	a
Whorl count	0.0427	0.1439	a
Vertex	-0.0794	0.0084	r

Table 18: Means and associated probabilities for each measurement method's differences in MIX from the MIX estimated by the climbing method. The probabilities relate to the null hypothesis that mean = 0. The final column indicates whether the null hypothesis is accepted at the 95% level.

Table 19 shows the residual standard deviation for each of the 3 methods. These results indicate each of the methods have a relatively high variability in the differences between estimated MIX and MIX measured by the climbing method.

METHOD	STANDARD DEVIATION
Height pole	0.1719
Whorl count	0.1996
Vertex	0.2083

Table 19: Residual standard deviations for each of the 3 methods. The residual values are based on the difference between the height pole and vertex methods, and the climbing method estimates of MIX.

The plots of residual values against estimated MIX for each of the 3 methods are given in Appendix II. These plots indicate the level of difference in MIX estimates between the height pole and vertex, and the climbing method do not change for different estimates of MIX. There is a slight trend in the whorl count residuals. The whorl count method tends to overestimate at low MIX and underestimate at high MIX. The level of differences are larger than those for MIL estimates. These larger differences may be due to MIX estimates being strongly influenced by both the identification of the number of whorls and the measurement of whorl location on the stem.

Figure 10 shows the average residual internode length for 1 m height intervals up the stem from 0.0 m to 12.0 m.

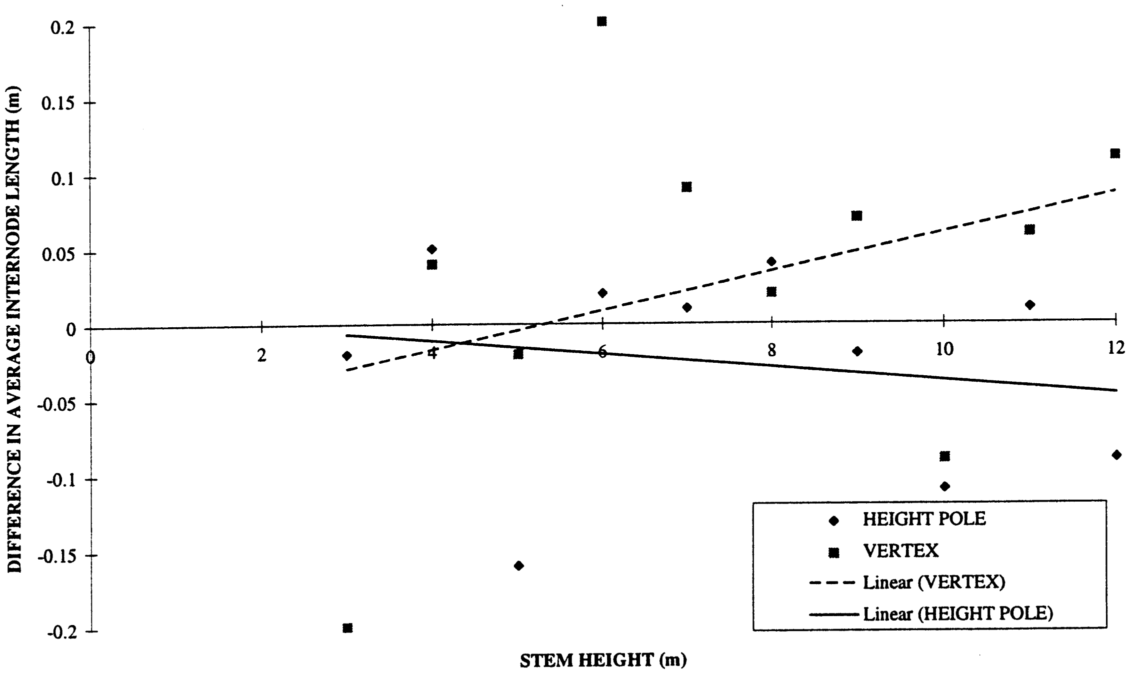

Fig. 10. Average residual internode length (m) occurring in 1 m height classes on the tree stem from 0.0 m to 11.0 m for the vertex and height pole internode length measurement techniques compared with the climbing method.

The results of the regression analysis (Table 20) of the residuals against stem height indicate the vertex and height pole methods do not suffer significantly from errors due to parallax, in estimates of internode length in the higher sections of the stem.

METHOD	SLOPE	LOWER 95%	UPPER 95%	P-VALUE	
Height pole	-0.0045	-0.0230	0.0139	0.59	not significant
Vertex	-0.1945	-0.2929	0.6819	0.38	not significant

Table 20: Estimated slope and 95% confidence interval for the slope estimate. The P-value is the probability that the slope of the trend line is zero.

The height pole commonly overestimates height to the base of the whorl on the lower sections of the stem from 6 to 10 m (Figure 11). There is no obvious tendency to over or underestimate height to whorl base at any other level on the stem.

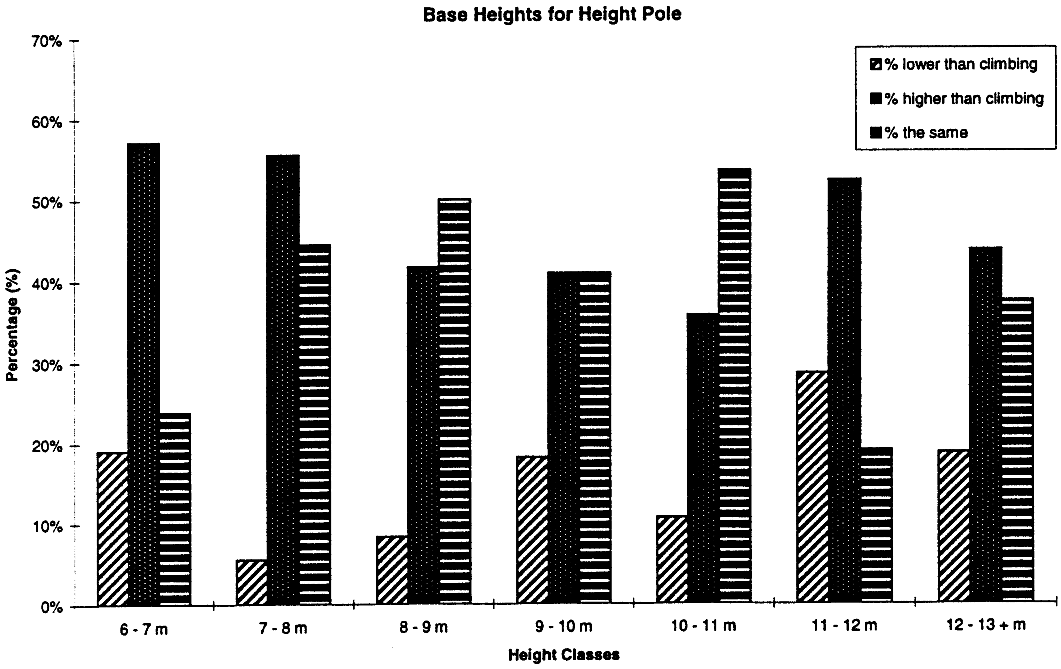

Fig 11: Percentage occurrence of over or underestimation of height to base of whorl measured by the height pole compared with the climbing method, by 1 m height classes. Estimates of height to the base of the whorl were considered the same if the were within ±0.05 m.

The vertex commonly underestimates the height to the base of a whorl for whorls occurring in the 6 to 10 m stem section (Figure 12). Higher on the stem the vertex is more likely to measure the same height to the whorl base or overestimate the height.

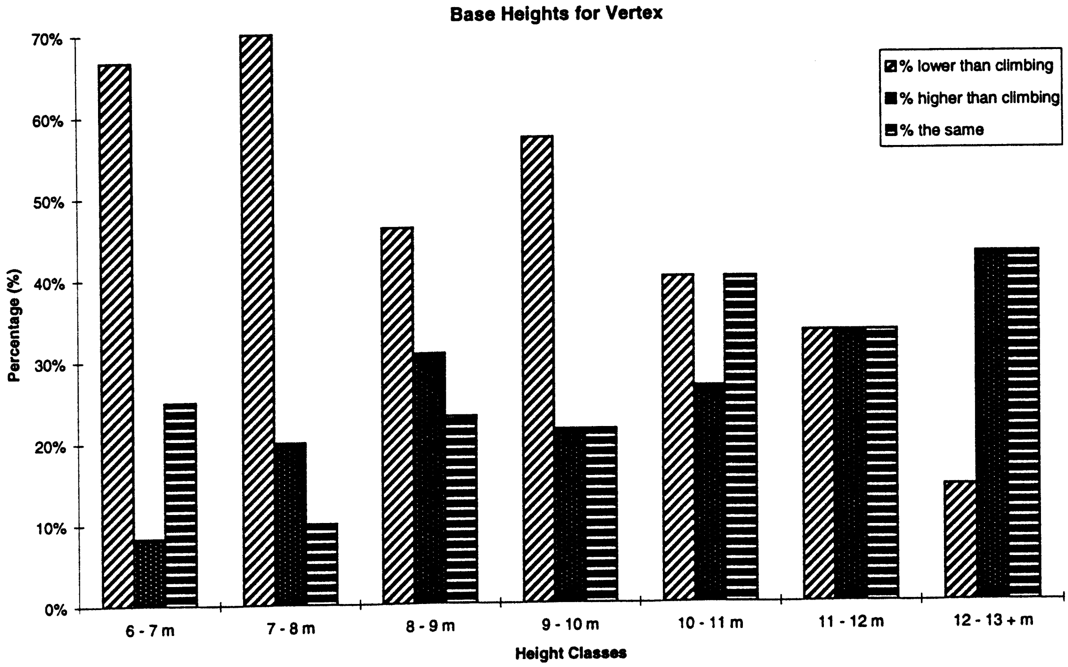

Fig 12: Percentage occurrence of over or underestimation of height to base of whorl measured by the vertex compared with the climbing method, by 1 m height classes. Estimates of height to the base of the whorl were considered the same if the were within ±0.05 m.

TIME

The relative ranking of the measurement methods in terms of number of trees that can be measured in an hour is given in Table 22. The values given in Table 22 are indicative only of the relative speed of each of the methods. As a result they are an indication of the relative ranking of each of the methods in terms of speed rather than an absolute measure.

MEASUREMENT METHOD	NUMBER OF TREES PER HOUR
Whorl Count	25
Forestor Vertex	15
Height Pole	11
Climbing	6

Table 21. Number of trees measured in an hour for the 4 measurement methods. These figures are based on being able to maintain the rate of measurement for an 8 hour day.

While the whorl count method is the most rapid method of appraising MIL. The Forestor vertex allows assessment of internode lengths at slightly more rapid rate per hour than the height pole. A week's work with the vertex would take approximately 2 extra days with the height pole. The use of the vertex allows significant time savings when internode length measurements are being made over several weeks. Based on a labour cost for 2 persons of $800/ week the vertex would recover its costs ($2,500 more than a height pole) after 9 weeks if it was used instead of the height pole. This would be after measuring 5 400 trees compared with 3 960 trees measured by the height pole. While on the issue of speed of measurement, it is important to note that measuring more trees using a particular method will not improve the level of bias in the estimate of stand MIL achieved with a particular method. A greater sample size will improve the level of precision associated with the estimated mean for a particular method.

SAFETY

Safety has always been an important issue, but is now, even more important with the Occupational Health and Safety Act (1991). All 4 methods of internode length measurement have health risks associated with them, however the potentially most dangerous is tree climbing. The issue of safety when tree climbing is discussed in Sections 25 to 28 in the Safety Code for Bush Undertakings Part 1 (Dept. of Labour, 1991). These sections are given in Appendix III. While Sections 25 to 28 do not specifically refer to tree climbing for branch measurement they are still relevant. The major influence of the requirements of the regulations is that any person climbing a tree must be secured at all times. This requires the use of a two safety belt system which slows the rate of climbing.

CONCLUSION

These results show the height pole to be the most appropriate means of MIL and MIX estimation for the genetic gain modifiers study (Turner *et al.* 1995). The height pole estimates of both MIL and MIX were the closest of any of the 3 methods to those made by the climbing method. The height pole estimates of MIL and MIX also are not significantly different to those made by climbing. The height pole also has the least variability in MIL and MIX estimates.

The whorl count method is an accurate and precise means of MIL estimation although individual estimates can differ greatly from the actual MIL. The whorl count estimate of MIX is relatively poor, although this could be improved by establishing a stronger relationship between MIL and MIX. The whorl count method , however, is not likely to be reliable for measurement of improved breeds for which there is no accurate estimate of average whorl depth.

While the tree climbing method is likely to be the most accurate method of estimating MIL and MIX for standing trees, it has certain drawbacks under the conditions in which this study was carried out:

- slow due to carrying a ladder and the 2 belt safety system (Dept. of Labour, 1991);
- still a relatively dangerous method;
- restricted more than the other methods by the weather conditions.

The vertex method has large differences from climbing in its estimates of MIL and MIX. Its estimates of MIL and MIX are also very variable. The advantage of the vertex is it enables more rapid measurement of internode lengths than the climbing or height pole methods.

An important area for further study would be to analyse how the methods of internode length measurement differ in their estimates of population variance in MIL and MIX. Such a study would require repeated measurement of the same trees using the 4 methods to gain an indication of the variation in estimated variance.

ACKNOWLEDGMENTS

John Penman, Richard Beamish-White, Hamish McElwee, Stephen Wakelin and Jeff Tombleson provided invaluable assistance with field work as well as giving advice on measurement techniques. Mark Dean provided information on the safety issues of tree climbing. Murray Lawrence gave instructions in the use of the Forestor Vertex and thank you to the Forestry Corporation of New Zealand for letting me use their Forestor Vertex. Dr Bruce Manley read through numerous draft copies and gave advice on analysis techniques. Mark Kimberley gave valuable advice on methods of statistical analysis. Leith Knowles, and Graham West read through and provided useful comments on draft copies. Jenny Grace suggested further means of comparing methods and gave useful comments on draft copies. Thanks to Pauline van Wijk for carrying out the laborious task of creating the plots of whorls for each tree.

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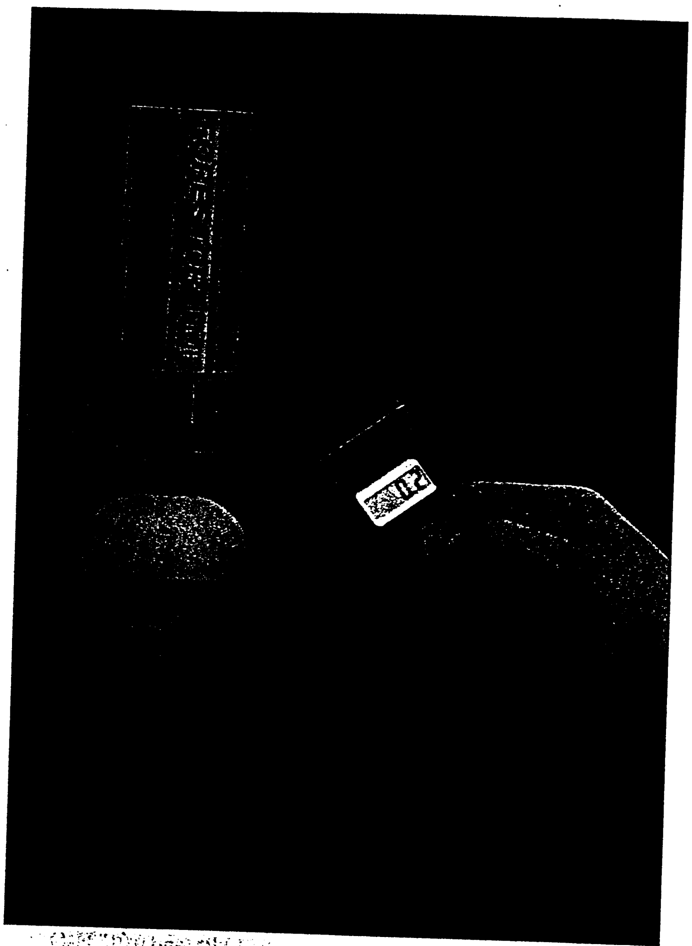
APPENDIX I: FORESTOR VERTEX DETAILS



Haglof Forestor DME 201

Save time and labor with this pocket-size, omni-directional, digital distance measurer! The Forestor DME 201 uses ultrasonic pulses to determine distance allowing you to walk 360° around the transponder and receive accurate measurements at the push of a button. There is no need for a tape measurer or two people, and because it uses ultrasonic pulses, you can shoot through brush and leaves! It's great for timber cruising, wildlife habitat plot sampling, stake-out measurements, building dimensions, lot dimensions, or anywhere else measurements are needed. The DME 201 can measure distance in English or metric and measures up to 30'/10m in normal conditions and up to 60'/20m in ideal conditions in feet and tenths/meters and centimeters with an accuracy of ±1%, and it can be easily calibrated. Two 9-volt batteries are required, one for the measuring instrument and one for the transponder. The Forestor DME 201 Complete Unit includes a measuring instrument, transponder, a plot center staff which extends to 60"L and retracts to 35"L, and a threaded tripod adapter for mounting the transponder on the plot center staff or on a standard photographic tripod. When ordering the transponder only, an adapter must be purchased separately.

09725	Forestor DME 201 – Complete Unit (1 lb.)	$649.00
09726	Distance Measuring Instrument Only (6 oz.)	$499.00
09727	Transponder Only – Adapter required (6 oz.)	$249.00
09728	Threaded Tripod Adapter Only (1 oz.)	$7.00
59708	Tripod (7.25 lbs.)	$168.00
02179	9 Volt Battery – 2 required (2 oz.)	$3.55

NEW!

Haglof VERTEX Hypsometer

Measuring tree heights has never been as fast and easy as it is now with the new Haglof VERTEX Hypsometer! With this new instrument, you will get the accurate measurements you need – from 0m/0' up to 100m/330'. The VERTEX Hypsometer is a lightweight instrument weighing only 10 ounces that fits in your pocket and allows you to measure tree heights through thick vegetation in either metric or English measurements. The metric/English scale is easily switched from one to the other.

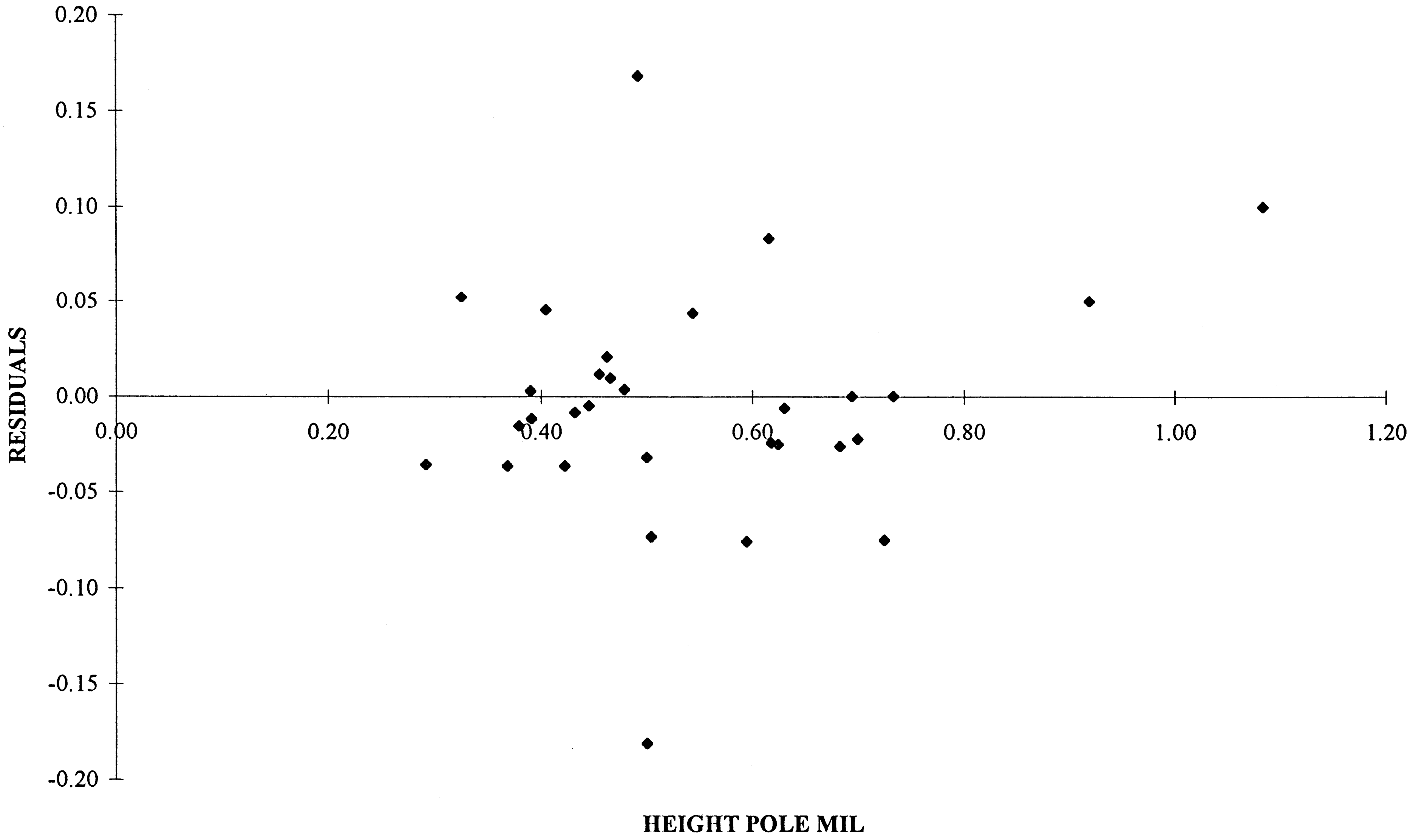
To use the VERTEX Hypsometer, simply fasten the omni-directional transponder to the tree to be measured at a suggested predefined height of 5'. With the fastening pin in the active position, the transponder is automatically switched on. Place the transponder on the tree, pointing it in the direction you are going, and find a location approximately as far away as the tree is high. You need to be able to see both the transponder and the top of the tree. Turn the hypsometer on, look through the sight aiming the red point at the transponder, press the red button keeping it pressed until the red point disappears, and then release the red button. You can now read on the display three numbers – distance, angle, and horizontal distance to the transponder. Aim at the top of the tree, press the red button and hold it. The total height of the tree will now show on the display. Two other points on the tree such as log lengths can also be measured in the same way. The VERTEX Hypsometer is easily calibrated and should be recalibrated every day for best accuracy. Complete user's instructions are included with each instrument.

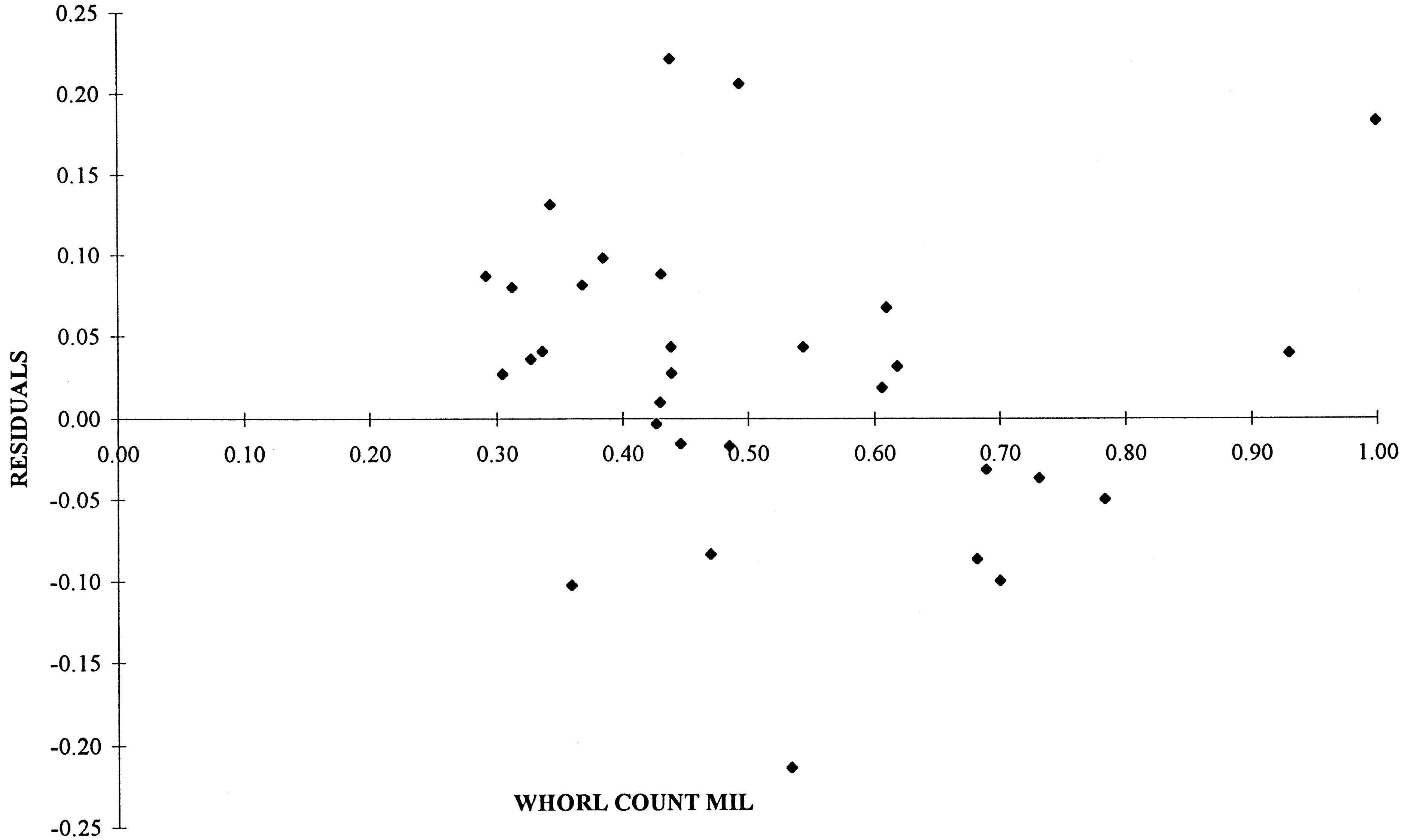
Hypsometer Specifications: Distance, 0-60m/0-197' with a resolution of 0.1m(<20m:0.01m); **Angle**, ±100 grad with a resolution of 0.1 grad; **Height**, 0-100m/0-330' with a resolution of 0.1m/0.1'; **Dimensions**, 4-3/4" x 2-5/8" x 1-1/2"; **Power**, 2 "AA" batteries.

The Transponder measures 1-5/8" x 5" and runs on one 9-volt battery.

09731	VERTEX Hypsometer/Transponder Package (1.5 lbs.)	$1,495.00
09729	VERTEX Hypsometer only (10 oz.)	$1,215.00
09730	Transponder only (7 oz.)	$275.00

APPENDIX II: RESIDUAL PLOTS


0.20
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
-0.20
RESIDUALS
0.00
0.20
0.40
0.60
0.80
1.00
1.20
HEIGHT POLE MIL


RESIDUALS
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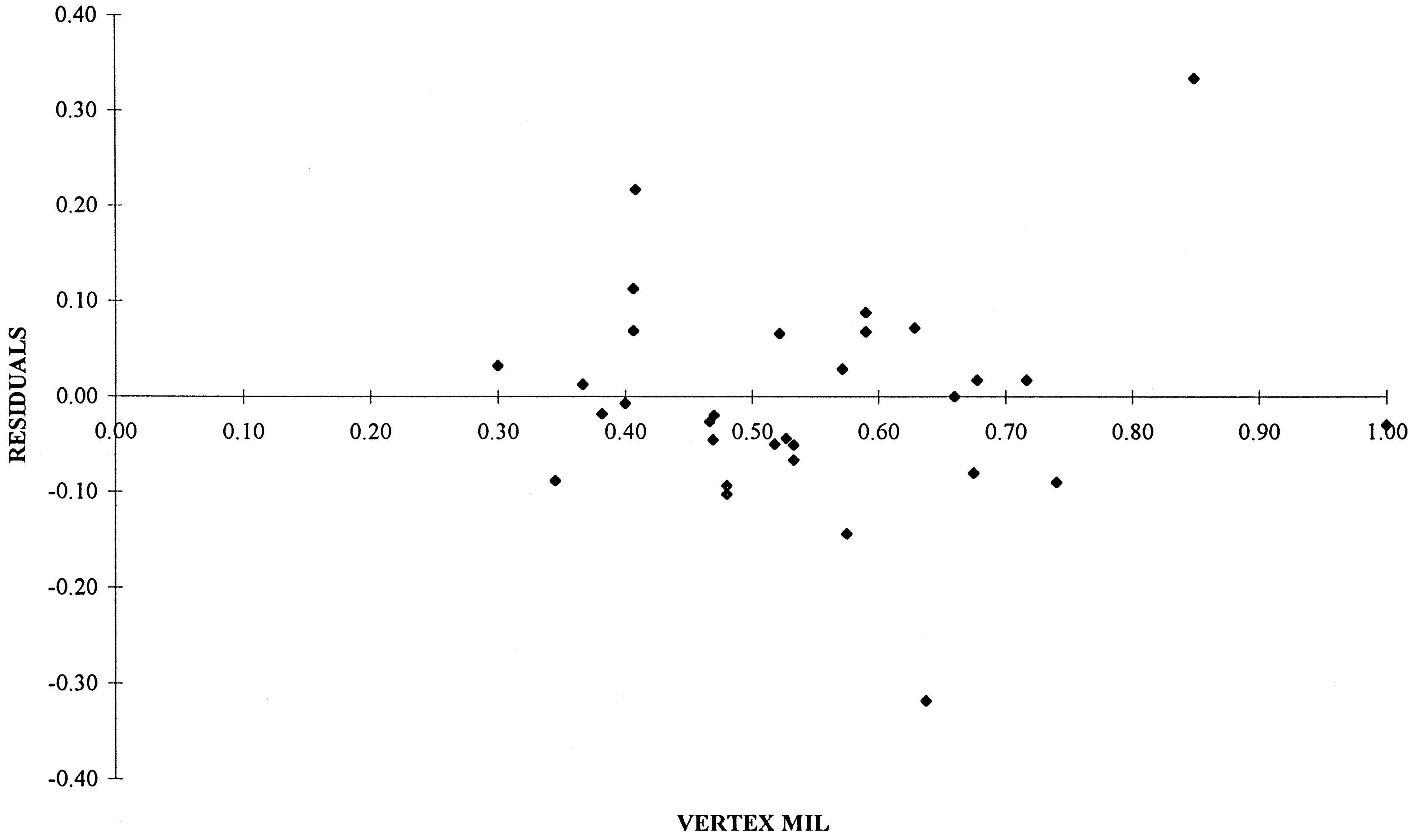
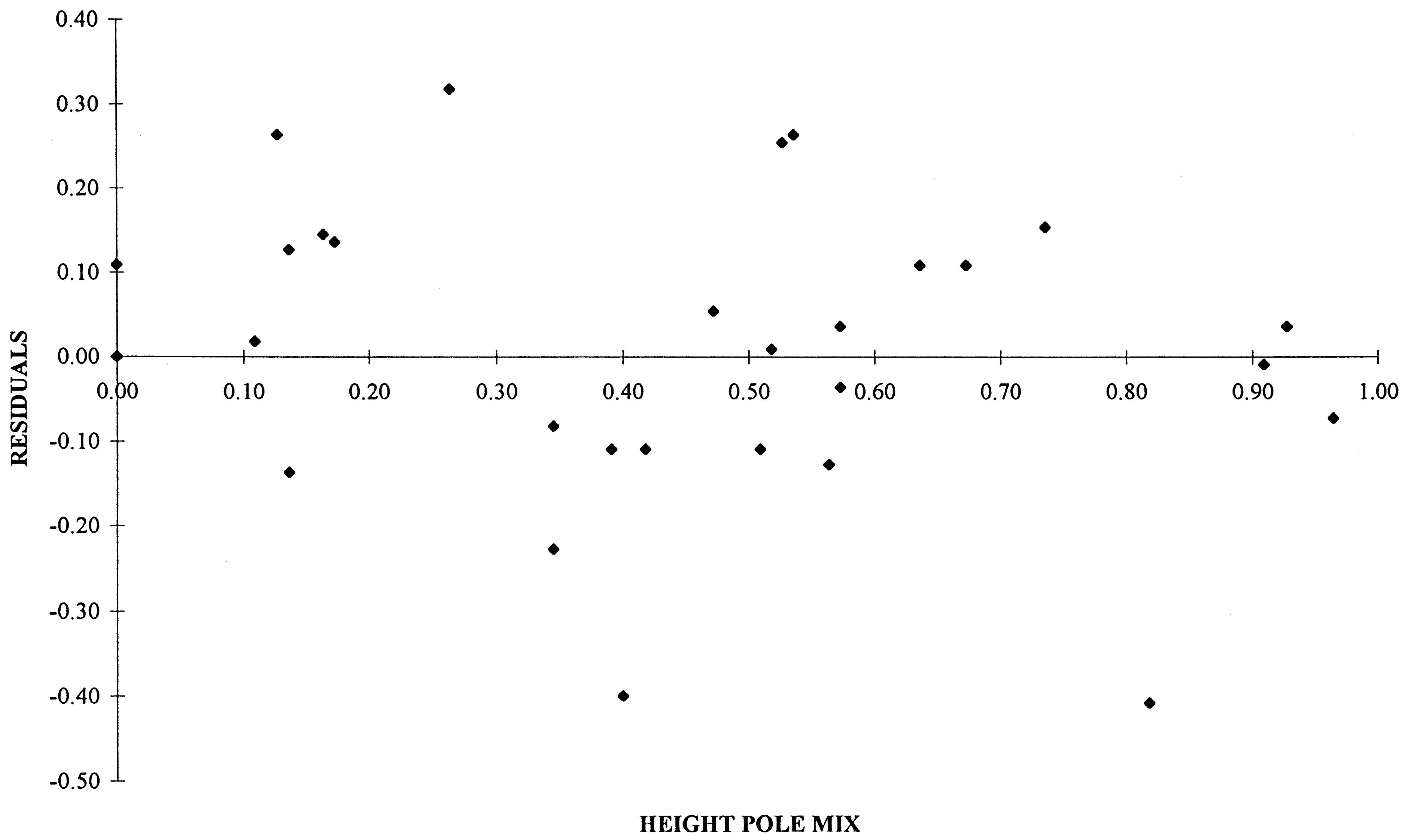
0.20
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
-0.20
-0.25
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
WHORL COUNT MIL


0.40
0.30
0.20
0.10
0.00
-0.10
-0.20
-0.30
-0.40
RESIDUALS
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
VERTEX MIL


RESIDUALS
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0.30
0.20
0.10
0.00
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-0.20
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-0.40
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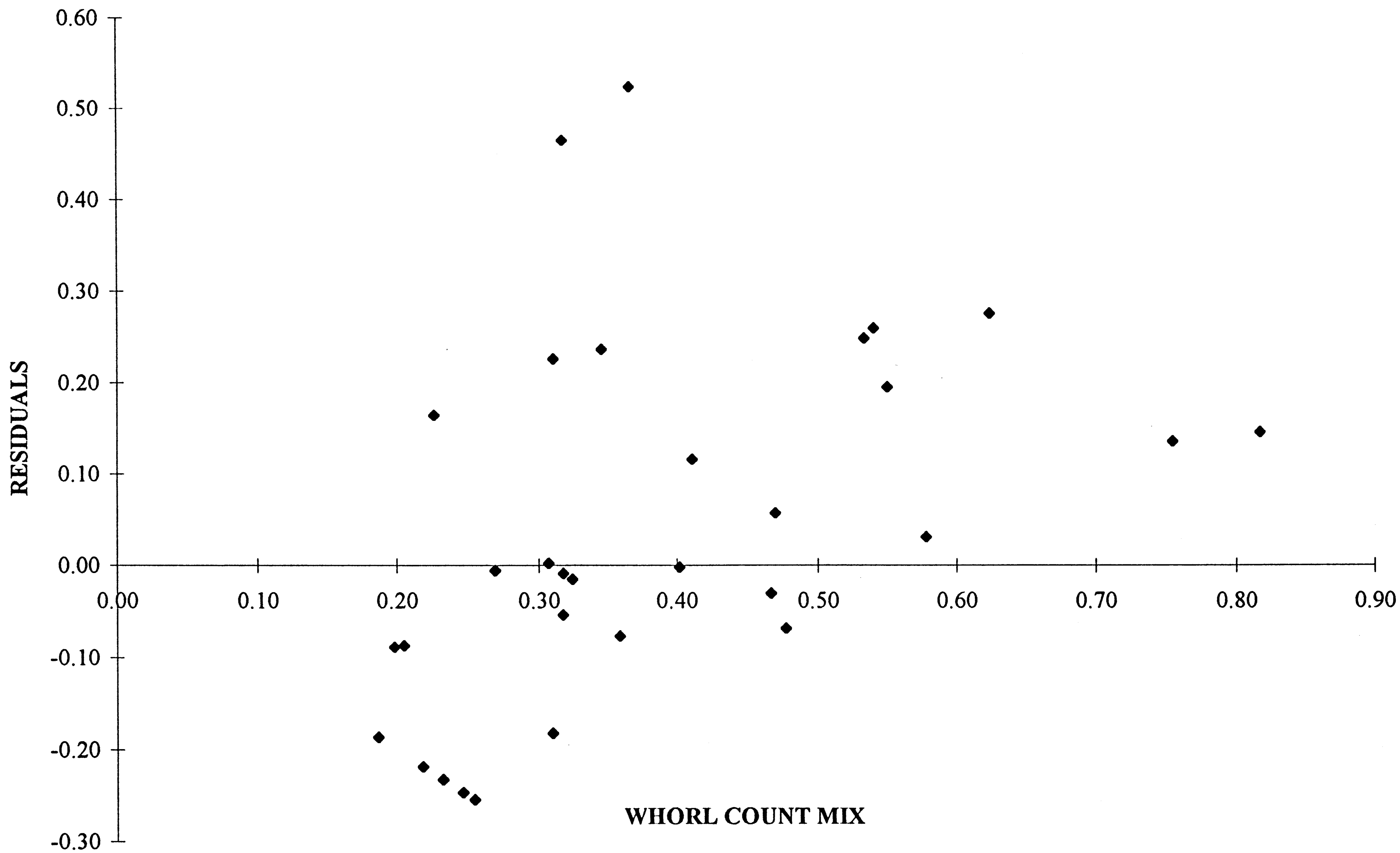
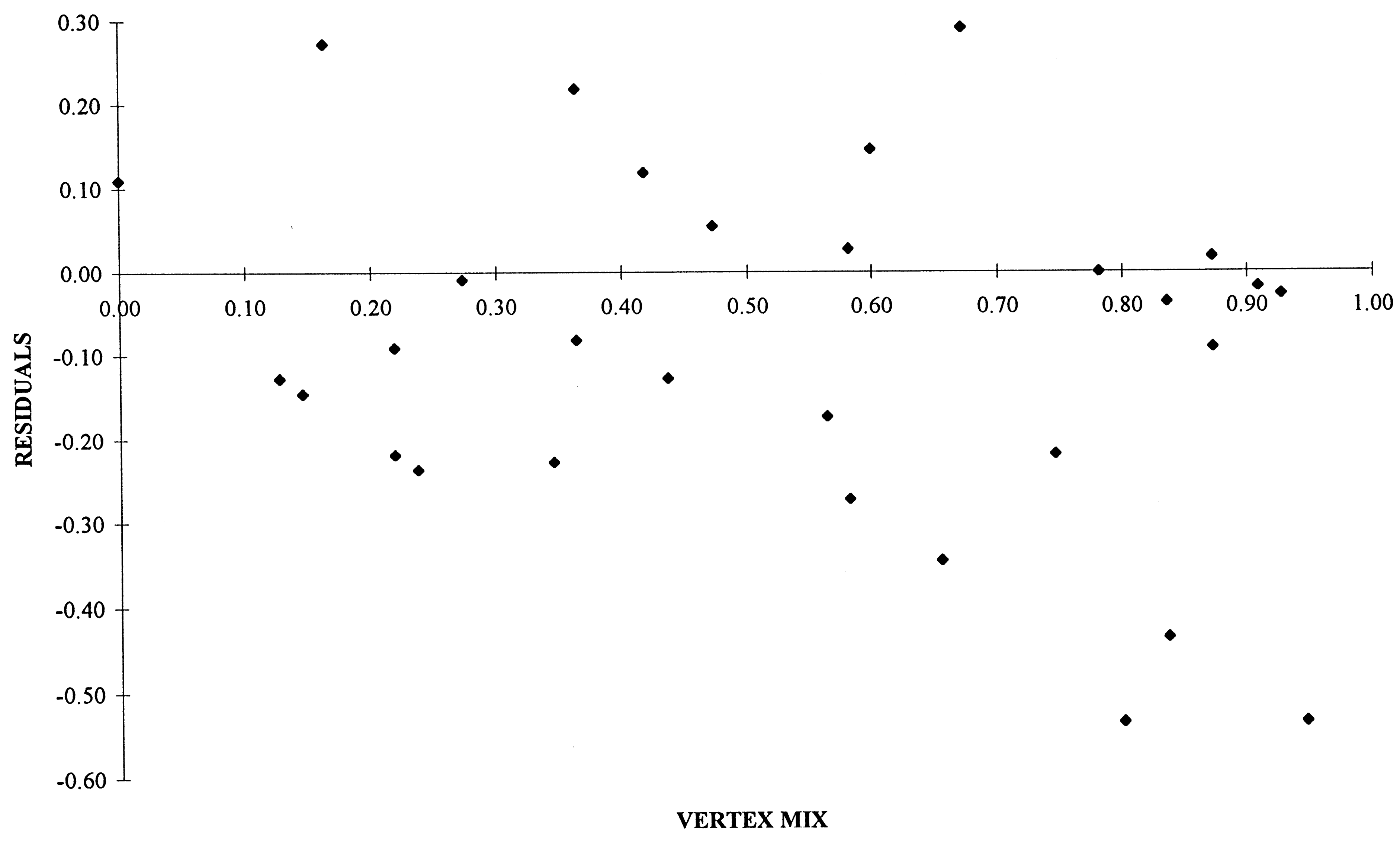
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
HEIGHT POLE MIX


RESIDUALS
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.10
-0.20
-0.30
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
WHORL COUNT MIX


0.30
0.20
0.10
0.00
-0.10
-0.20
-0.30
-0.40
-0.50
-0.60
RESIDUALS
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
VERTEX MIX

APPENDIX III: SECTIONS OF THE "SAFETY CODE FOR BUSH UNDERTAKINGS" RELEVANT TO TREE CLIMBING.

25. General Provisions

25.1 Never climb alone.

25.2 Avoid collection when winds are above 30km/h.

25.3 Clothing should be close fitting, with nothing loose to catch on branches.

25.4 Light footwear, e.g. sandshoes or basketball boots, is permissible.

25.5 Some form of head protection should be worn. Light bump hats are appropriate.

25.6 Do not over-fill collection bags.

25.7 Safety in the use of hiabs and cherry pickers is covered in section 43.

26. Safety Belts

26.1 Safety belts shall be worn above 5 metres in height.

26.2 Safety belts shall comply with the New Zealand standard specification in respect of manufacture, inspection, maintenance and storage.

26.3 Belts must be suitable for the job and have two climbing ropes, one of which must be secured at all times.

26.4 Safety belts shall be correctly fitted and adjusted to eliminate slack, as poorly fitted or loosely adjusted belts can cause significant bruising or more serious injuries in the event of a fall.

26.5 Never attempt to pick cones without the safety belt attached securely to a tree trunk.

26.6 When ascending or descending, the user's arms must be completely free of hand tools.

26.7 Hand tools, if carried by the user, shall be held in a properly constructed holder and be secured in such a way as to not impede the user's progress. Do not throw tools to the ground.

26.8 Keep feet close to the trunk of the tree when on branches.

27. Ladders

27.1 All ladders for use on seed collection shall comply with the New Zealand Standard.

27.2 Ladders shall be regularly checked and any defects repaired before being used. Particular attention should be given to the junction of the stiles and the rungs, interlocking joints and chains and pins.

27.3 When using ladders on sloping ground always work from the uphill side of the tree.

27.4 Always use both hands when ascending or descending a ladder. Do not jump.

28. Hazards

28.1 Hazards common to most types of seed collection are:

(a) Power lines.

(b) Dead or damaged branches.

(c) Portions of other trees lodged in the tree.

(d) Steeply sloping branches.

(e) Species with brittle branches.

(f) Wet and slippery conditions.

29. Seed Orchards—(except hedged orchards).

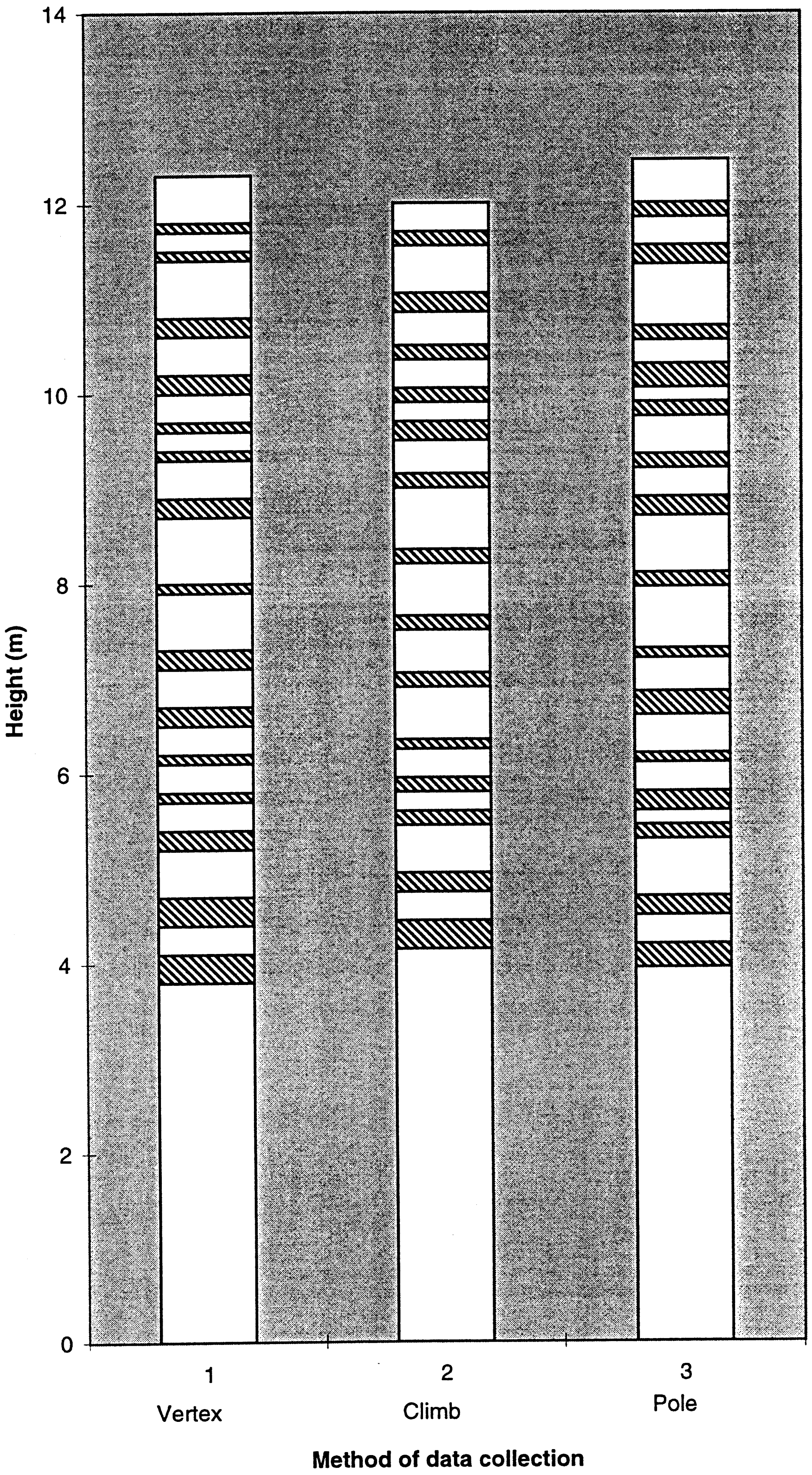
29.1 Pickers should wear some form of head protection. Light bump hats are appropriate.

29.2 All persons on the ground in the vicinity of picking operations shall wear a safety helmet to New Zealand Standard.

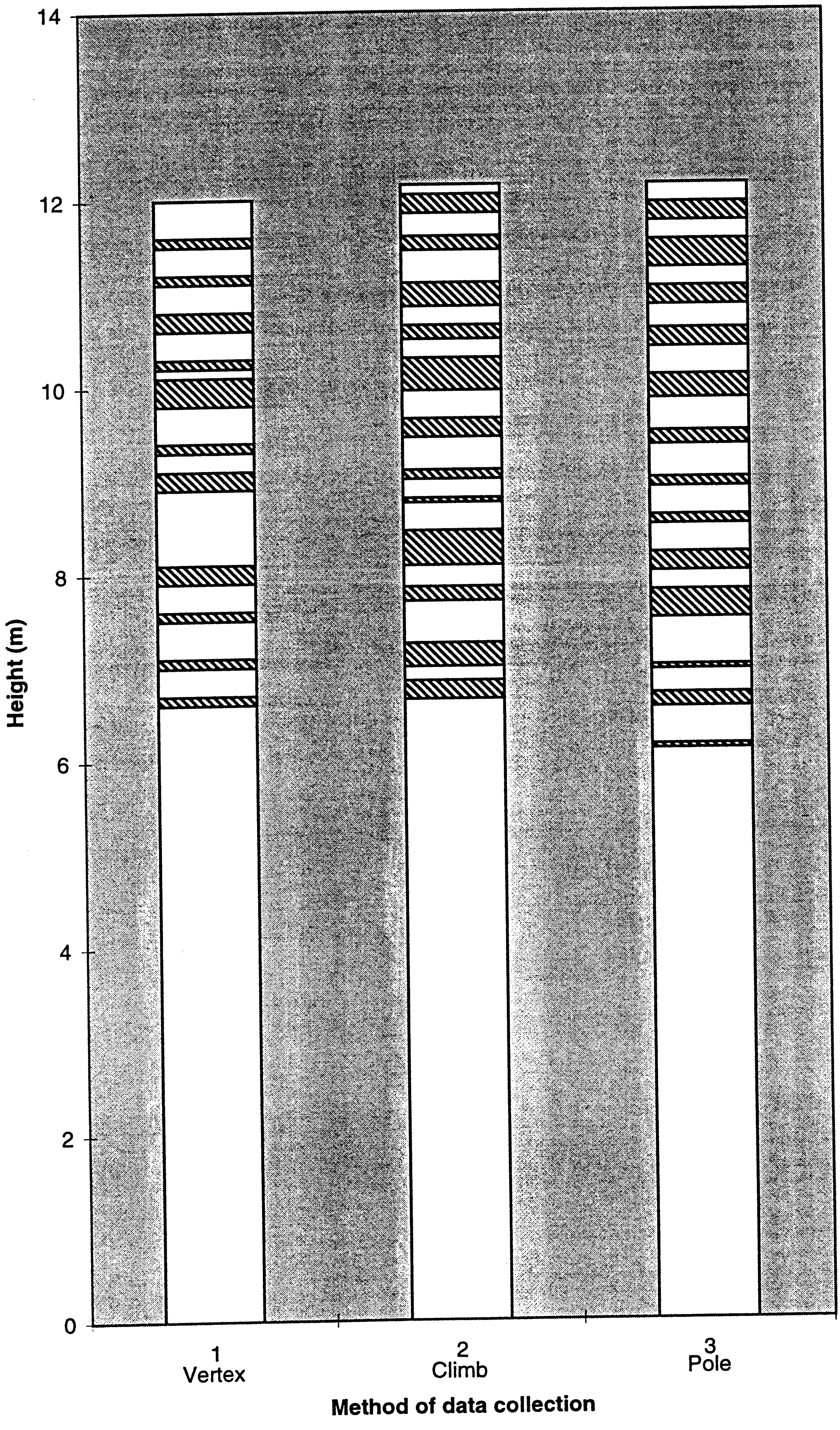
29.3 Provisions of section 50 of this code must be complied with while using a power-operated elevating work platform.

APPENDIX IV: INDIVIDUAL TREE PROFILES FOR EACH OF THE MEASUREMENT TECHNIQUES.

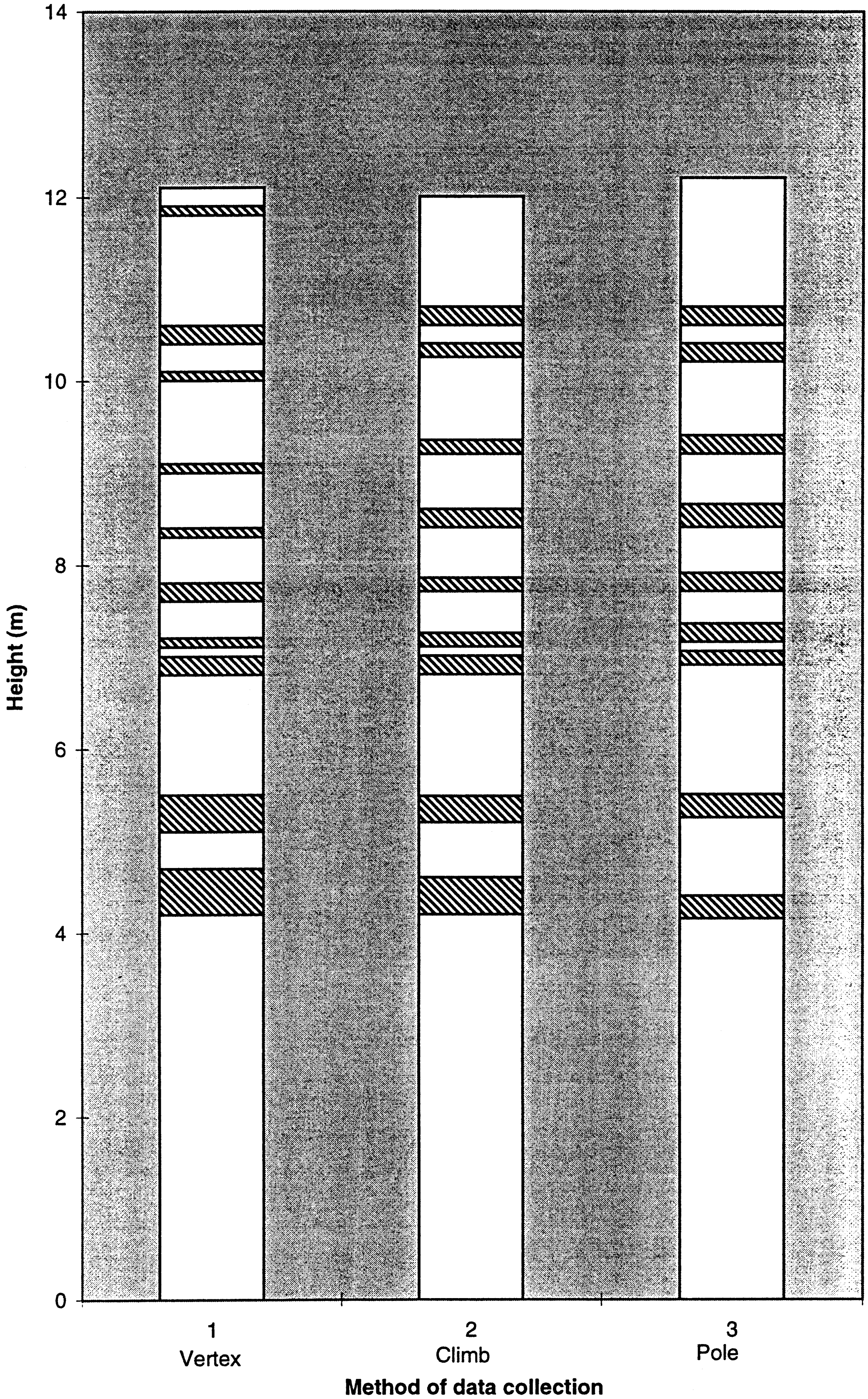
Branch Profile for Tree 15



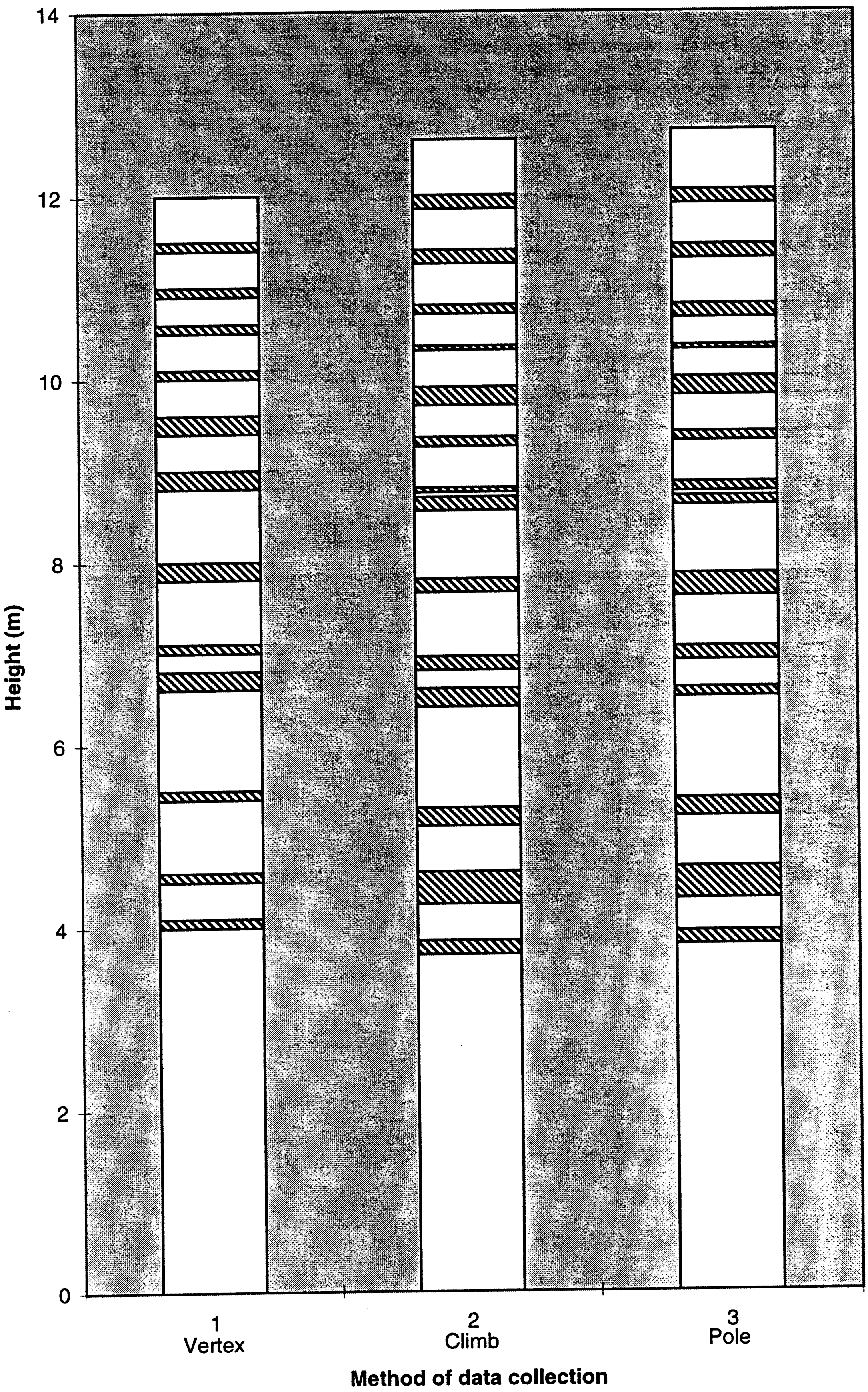
Branch Profile for Tree 16



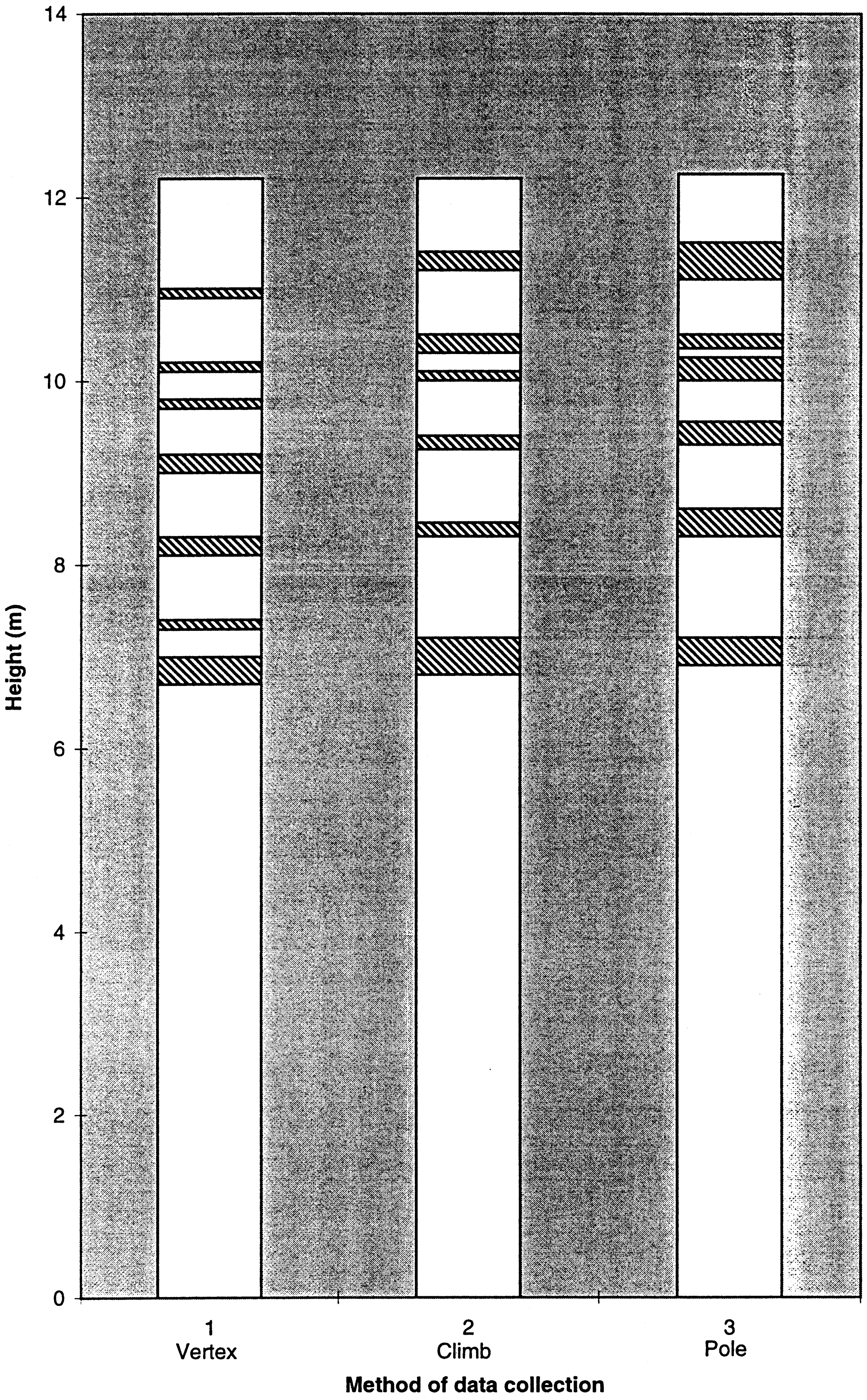
Branch Profile for Tree 18

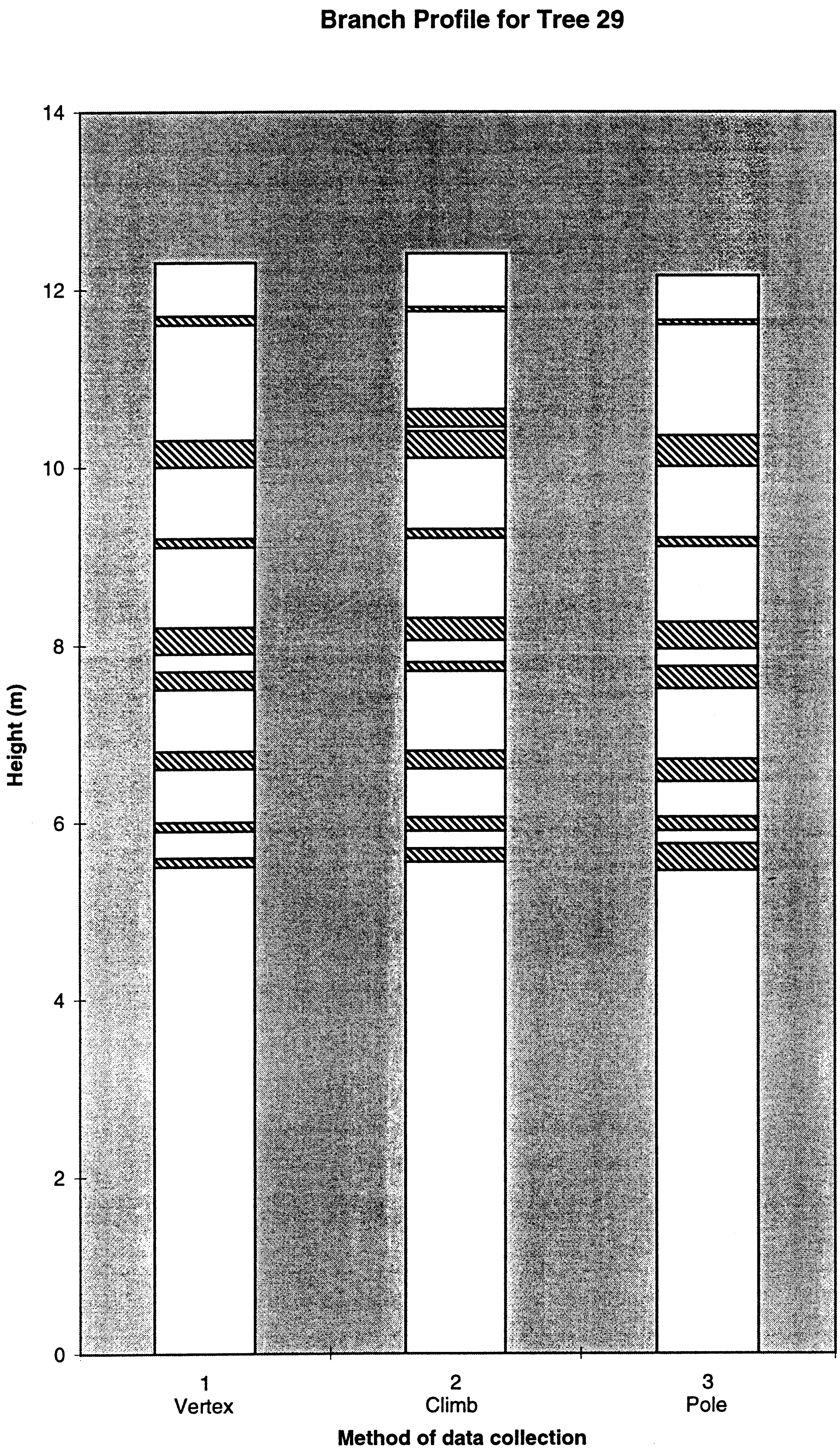


Branch Profile for Tree 22

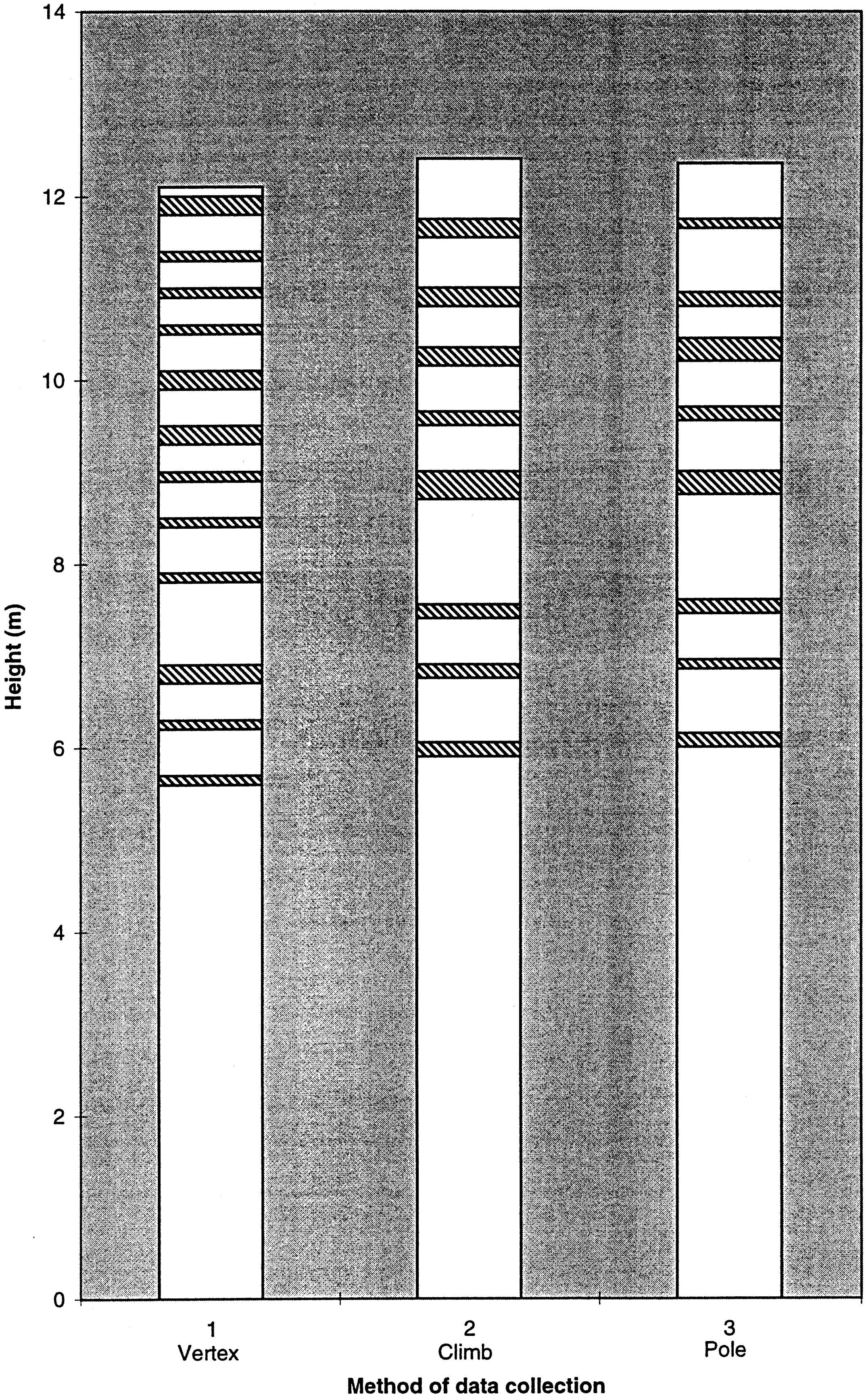


Branch Profile for Tree 26

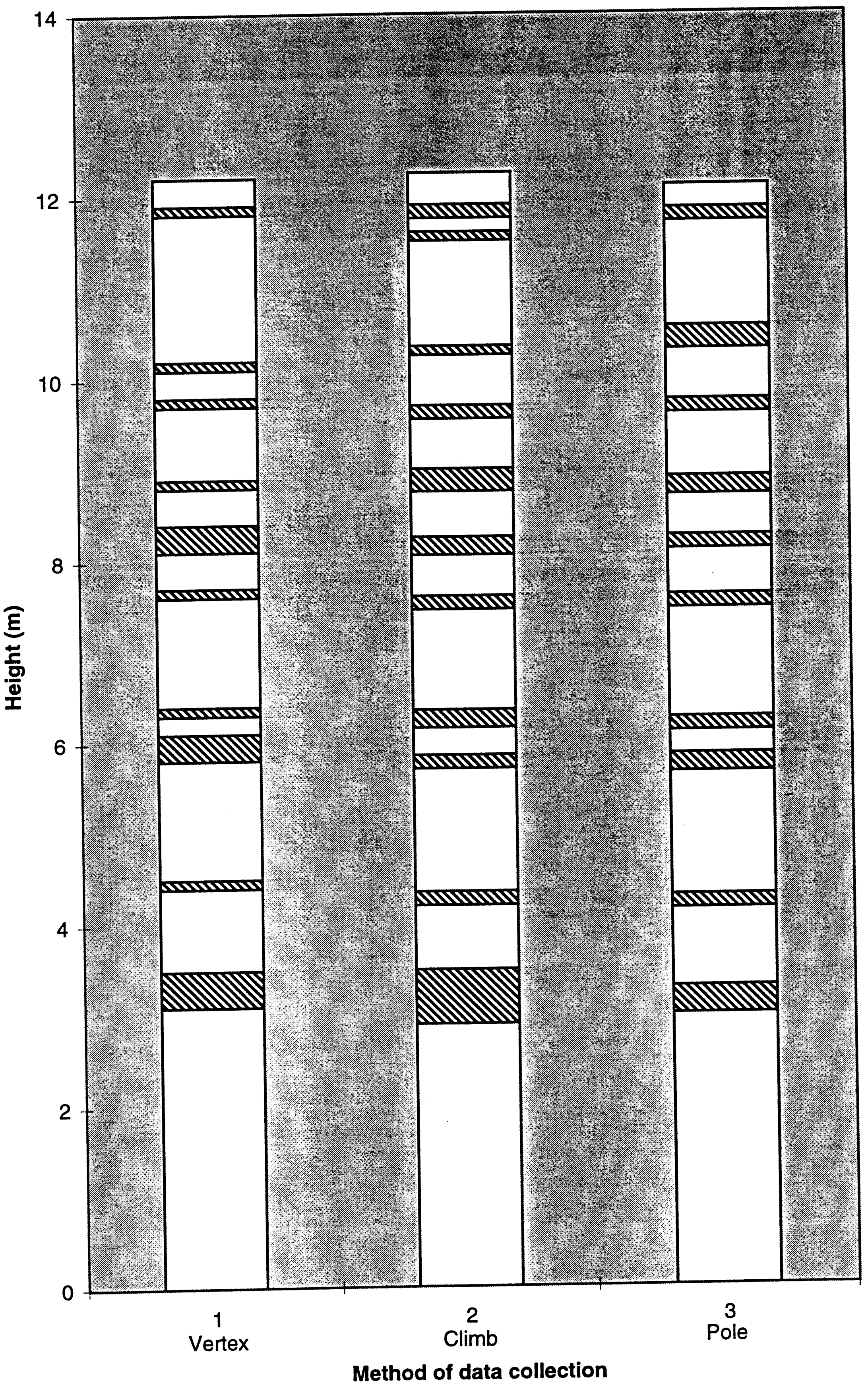



Branch Profile for Tree 29
Height (m)
0
2
4
6
8
10
12
14
1
Vertex
2
Climb
3
Pole
Method of data collection

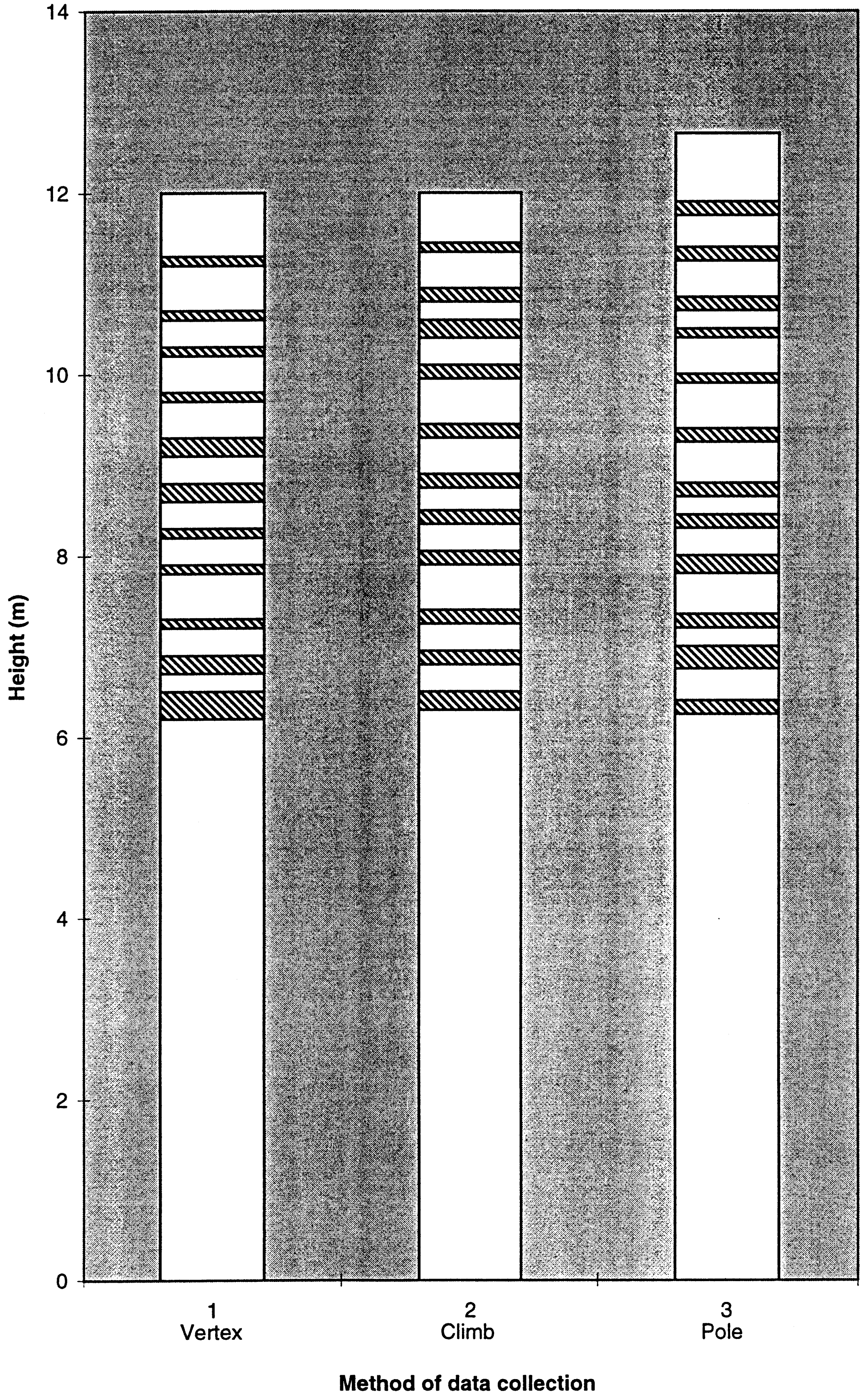
Branch Profile for Tree 32

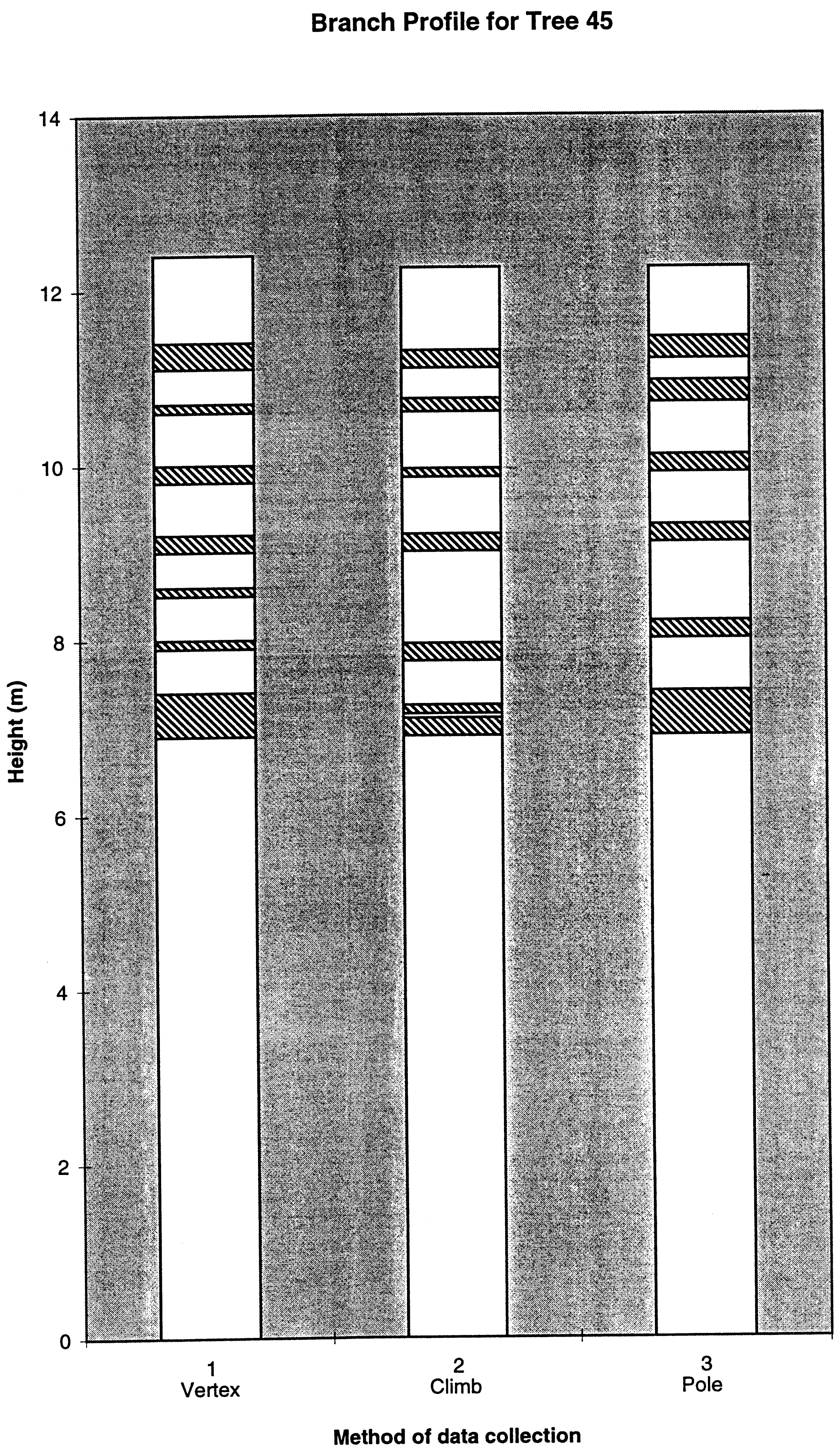


Branch Profile for Tree 34



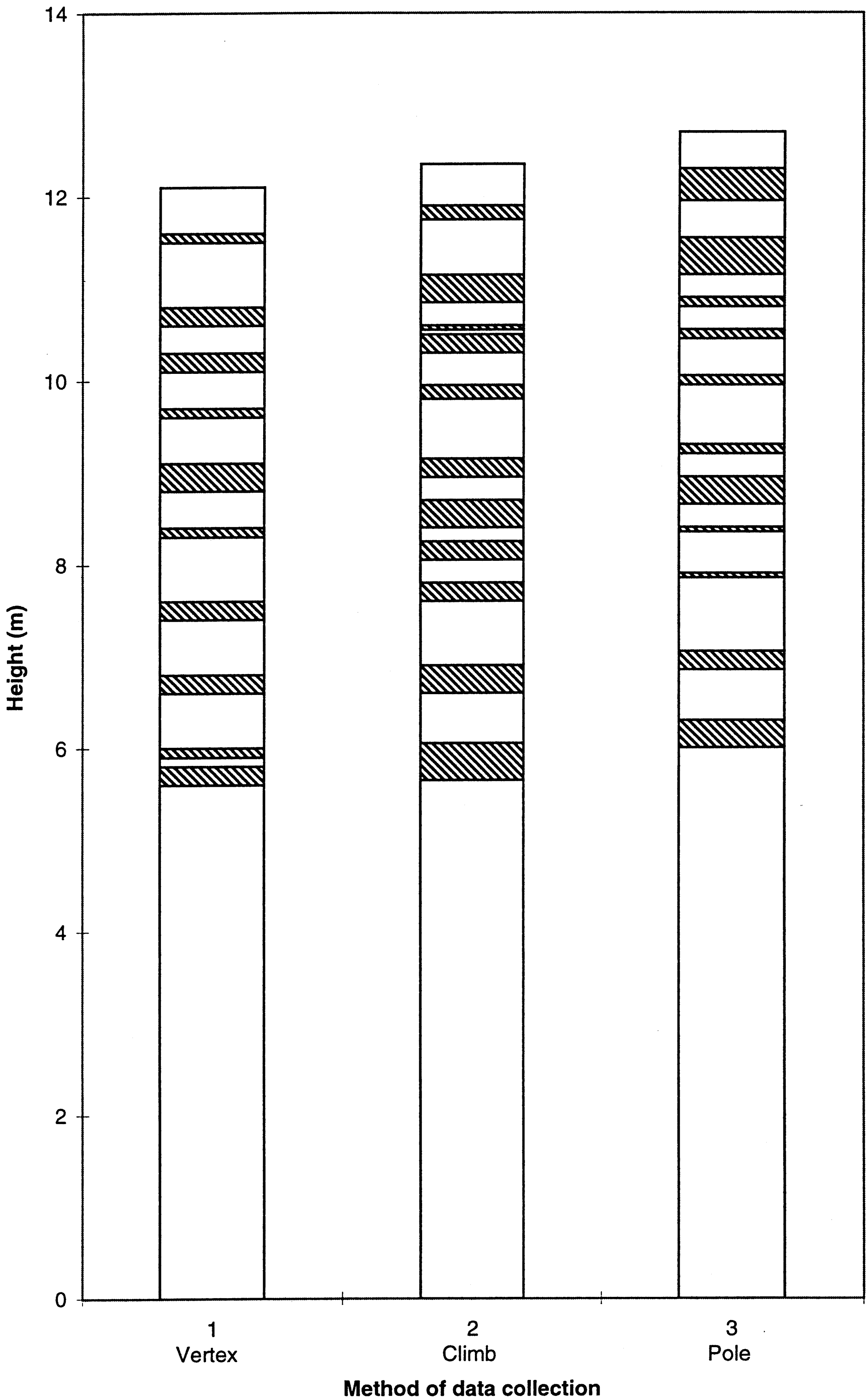
Branch Profile for Tree 39

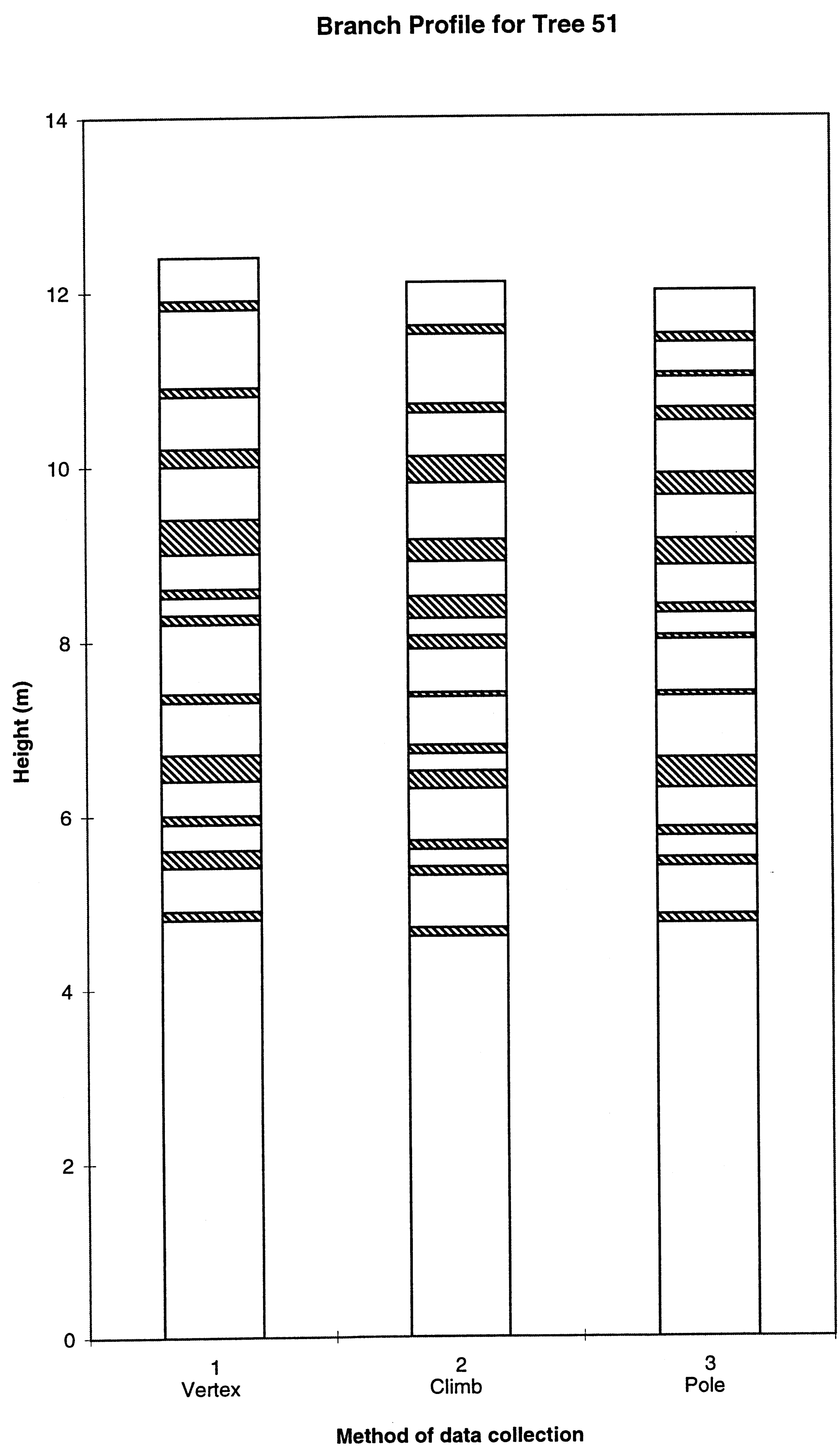


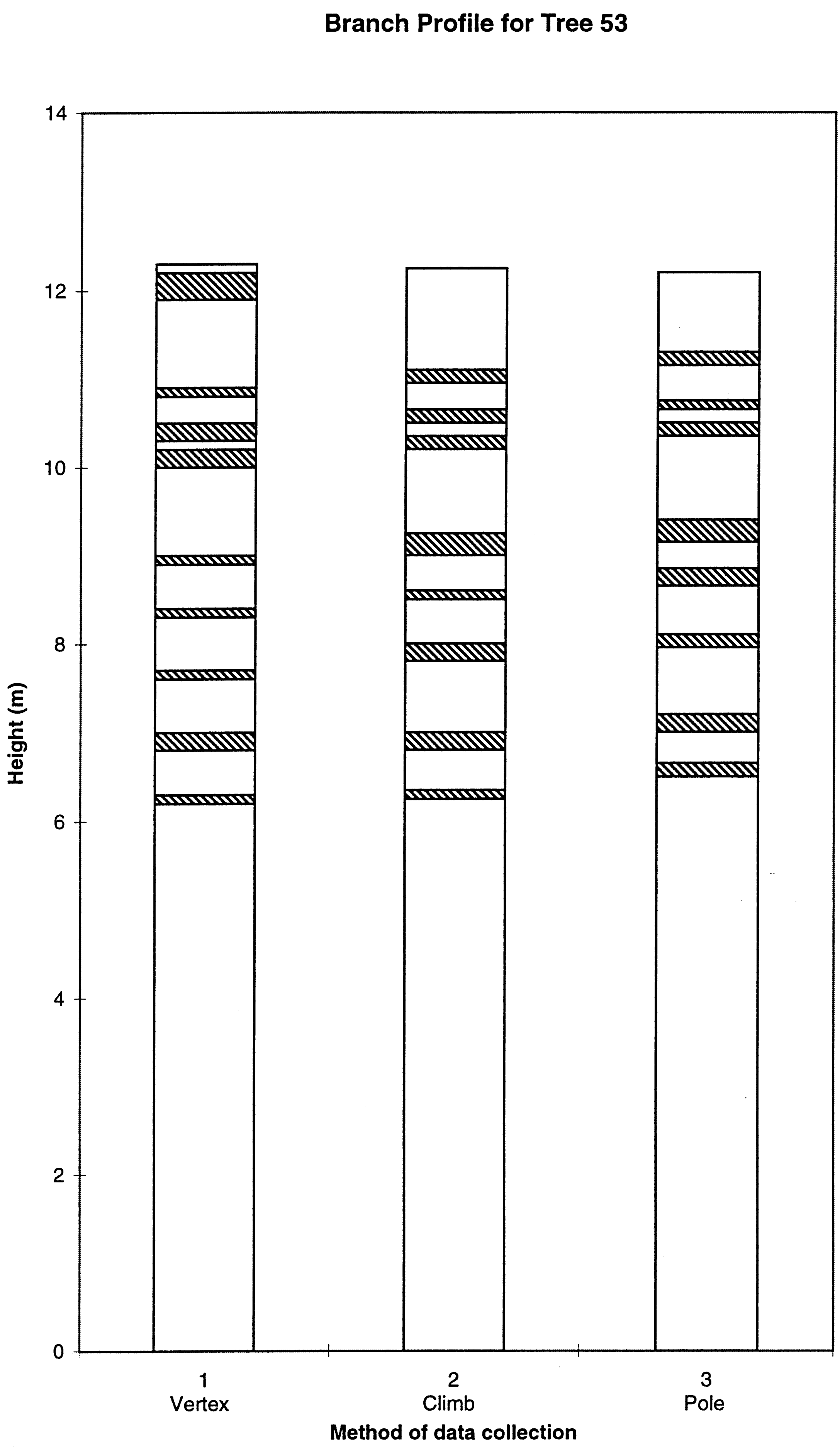


Branch Profile for Tree 45
14
12
10
8
6
4
2
0
Height (m)
1
Vertex
2
Climb
3
Pole
Method of data collection

Branch Profile for Tree 47

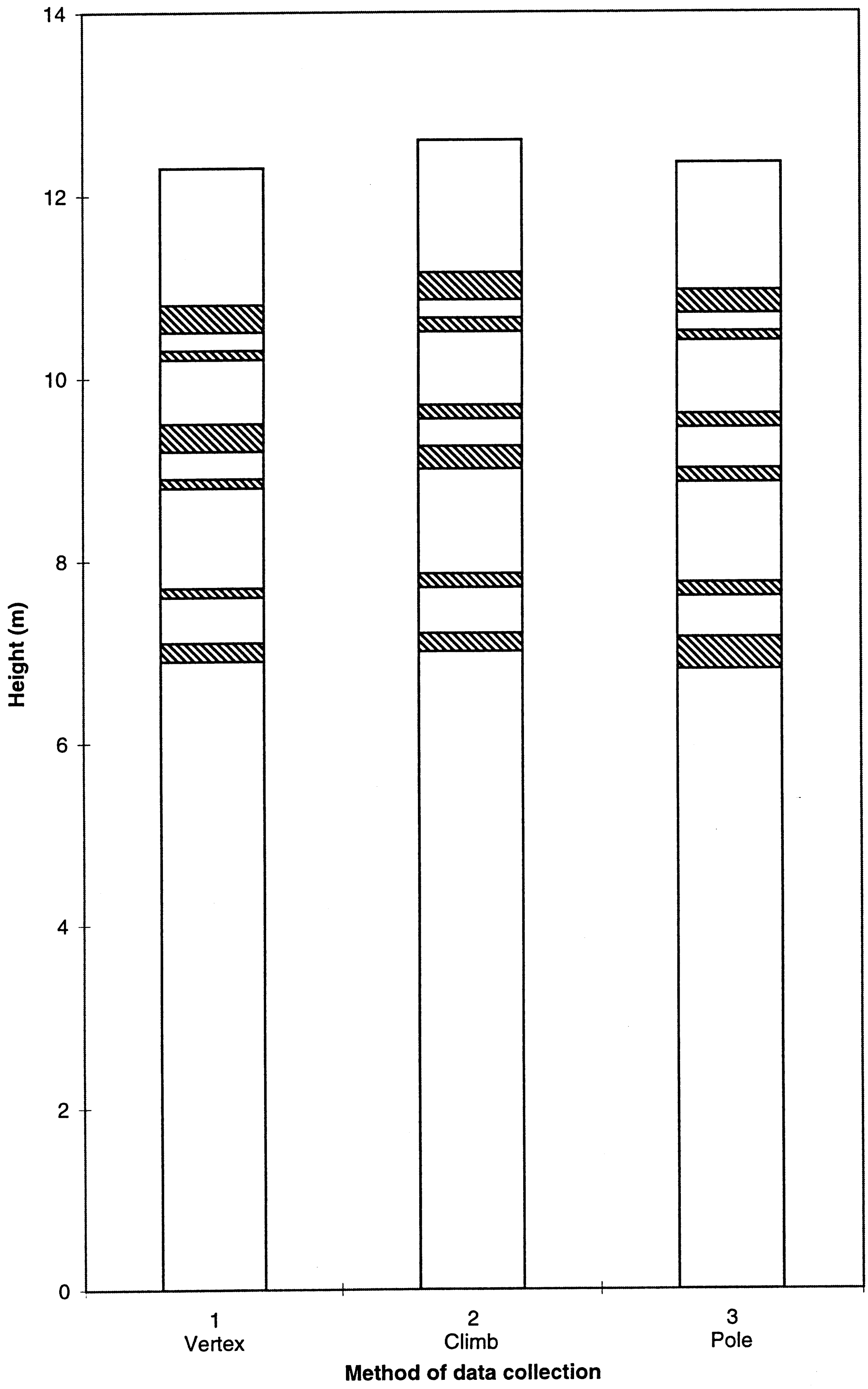



Branch Profile for Tree 51
Height (m)
14
12
10
8
6
4
2
0
1
Vertex
2
Climb
3
Pole
Method of data collection

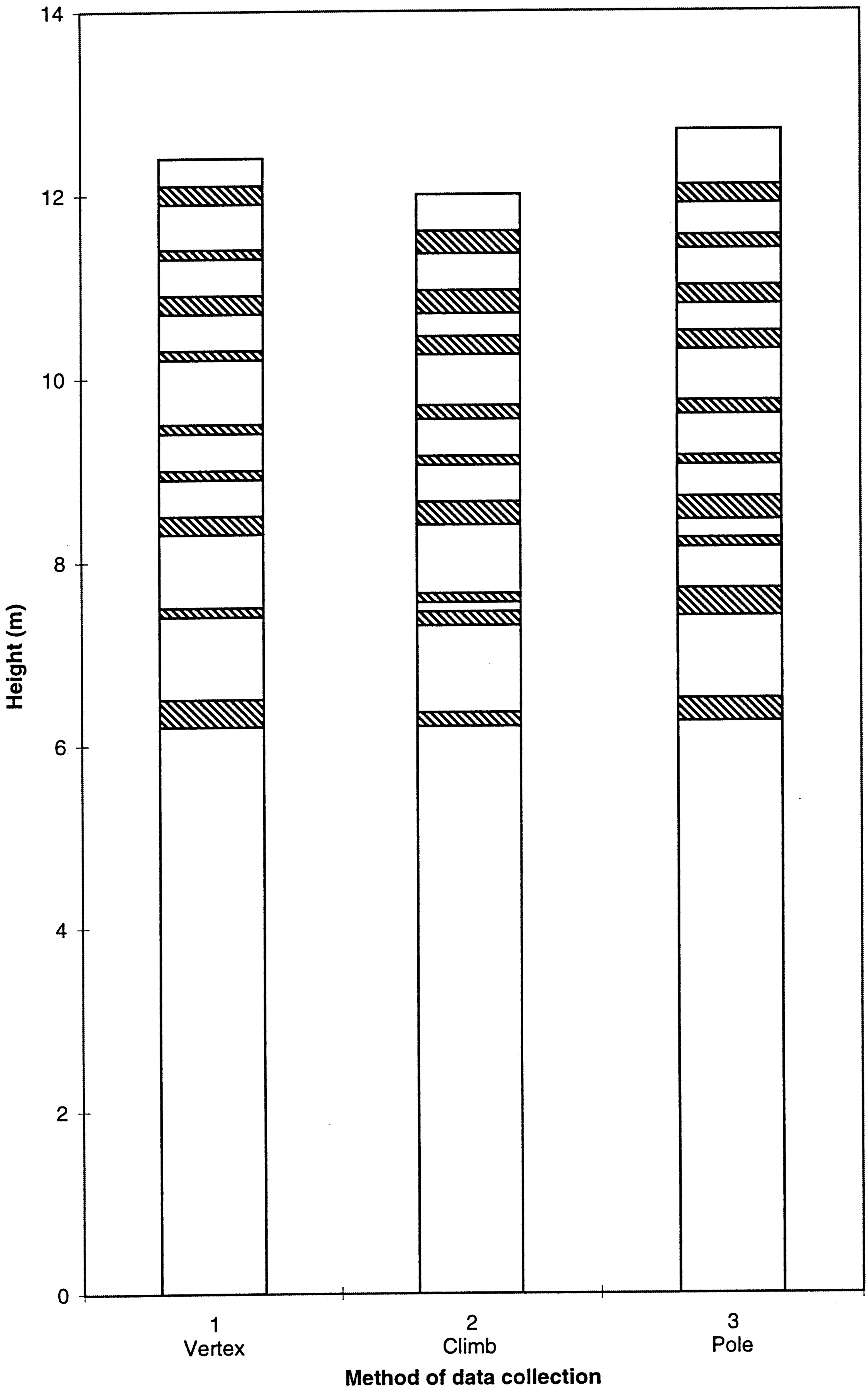


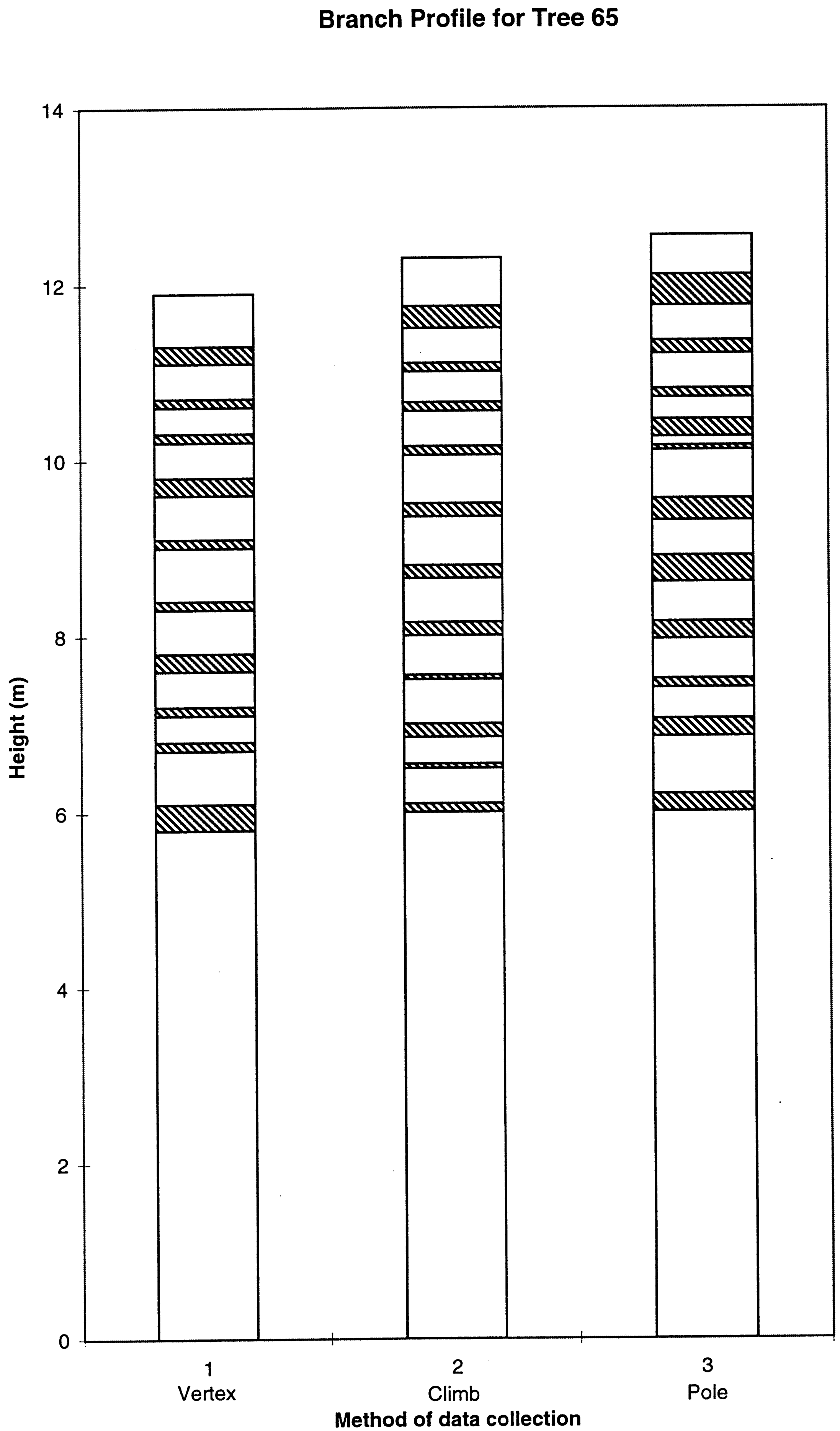
Branch Profile for Tree 53
Height (m)
0
2
4
6
8
10
12
14
1
Vertex
2
Climb
3
Pole
Method of data collection

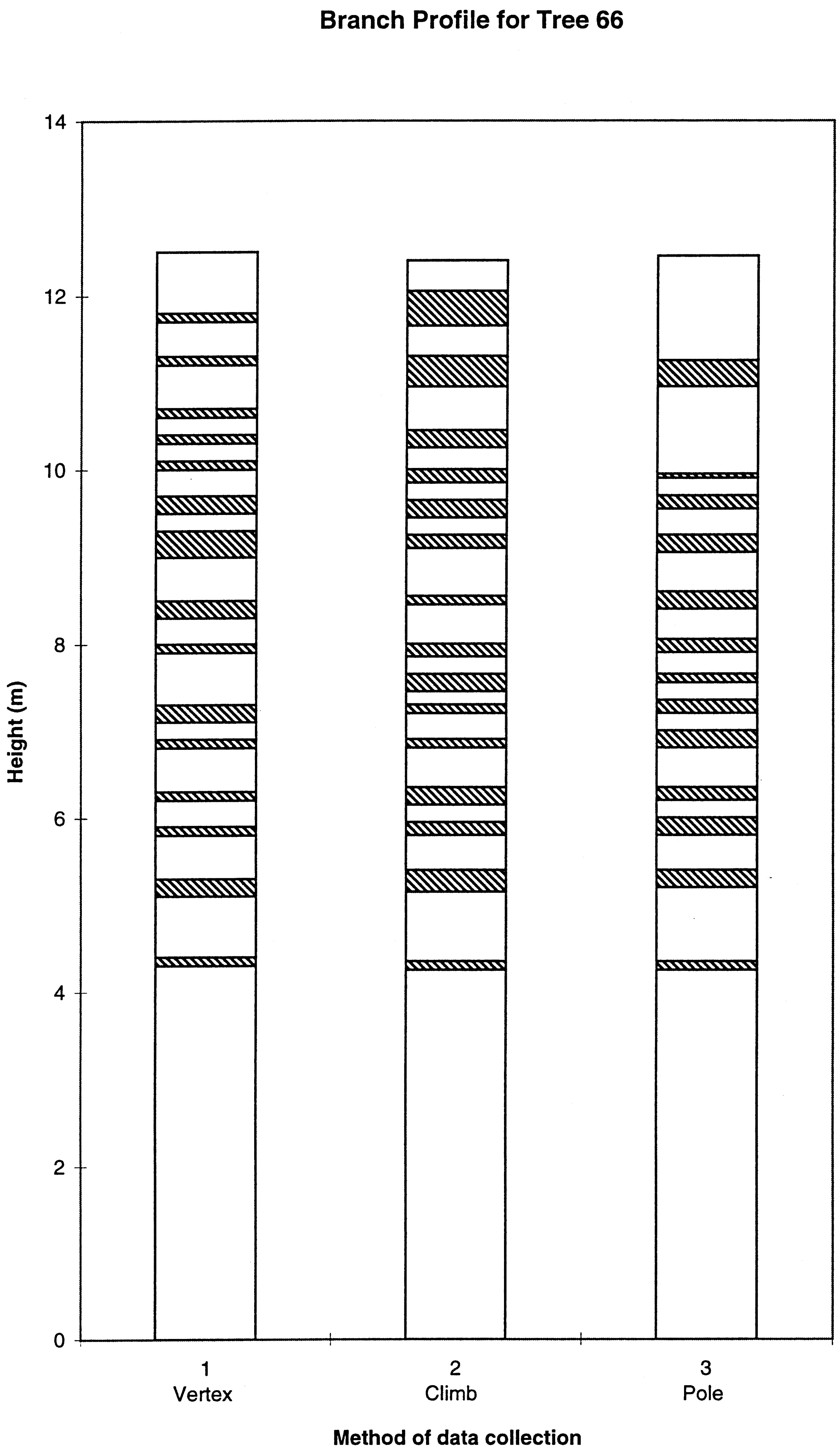
Branch Profile for Tree 59

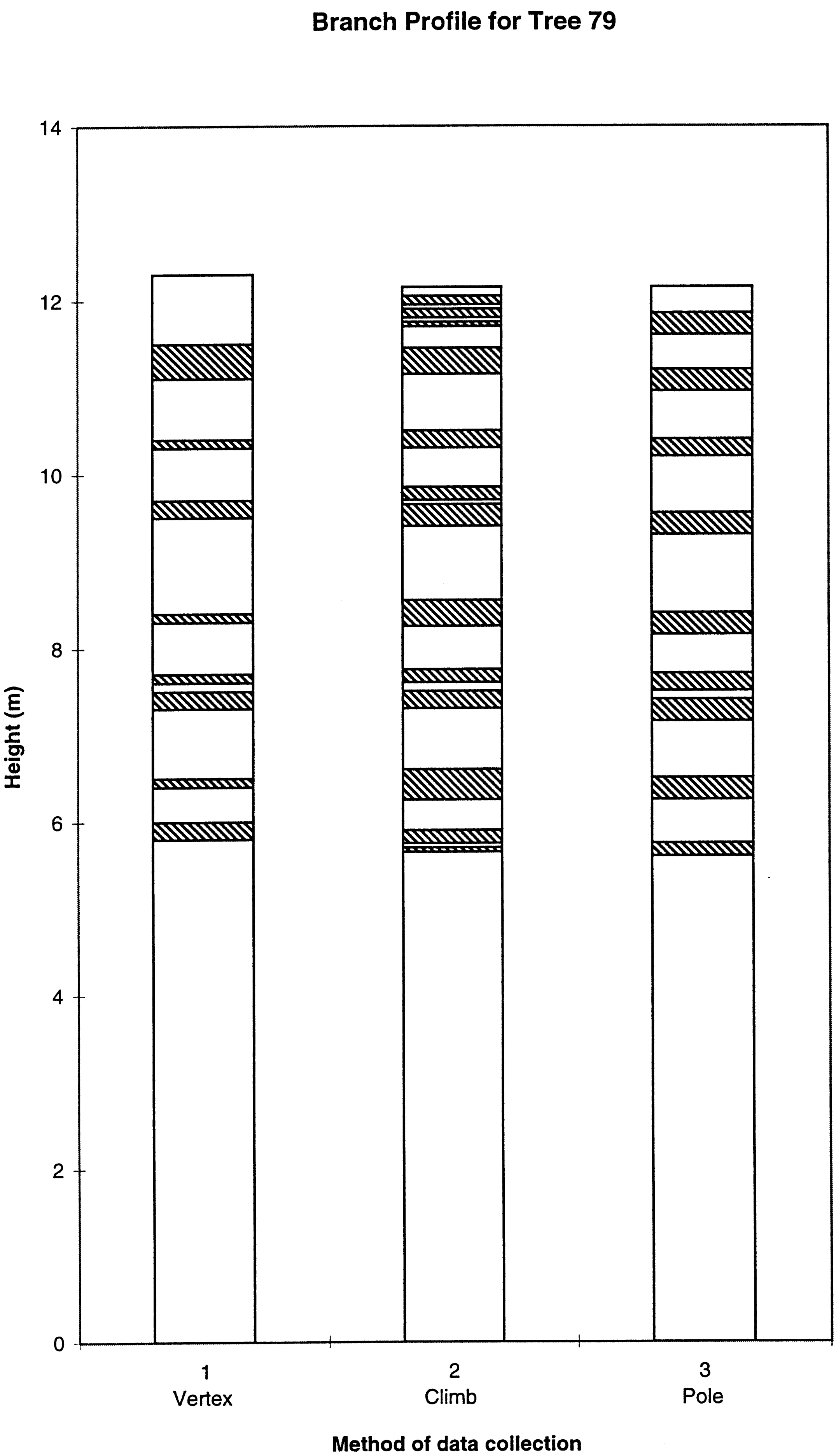


Branch Profile for Tree 61

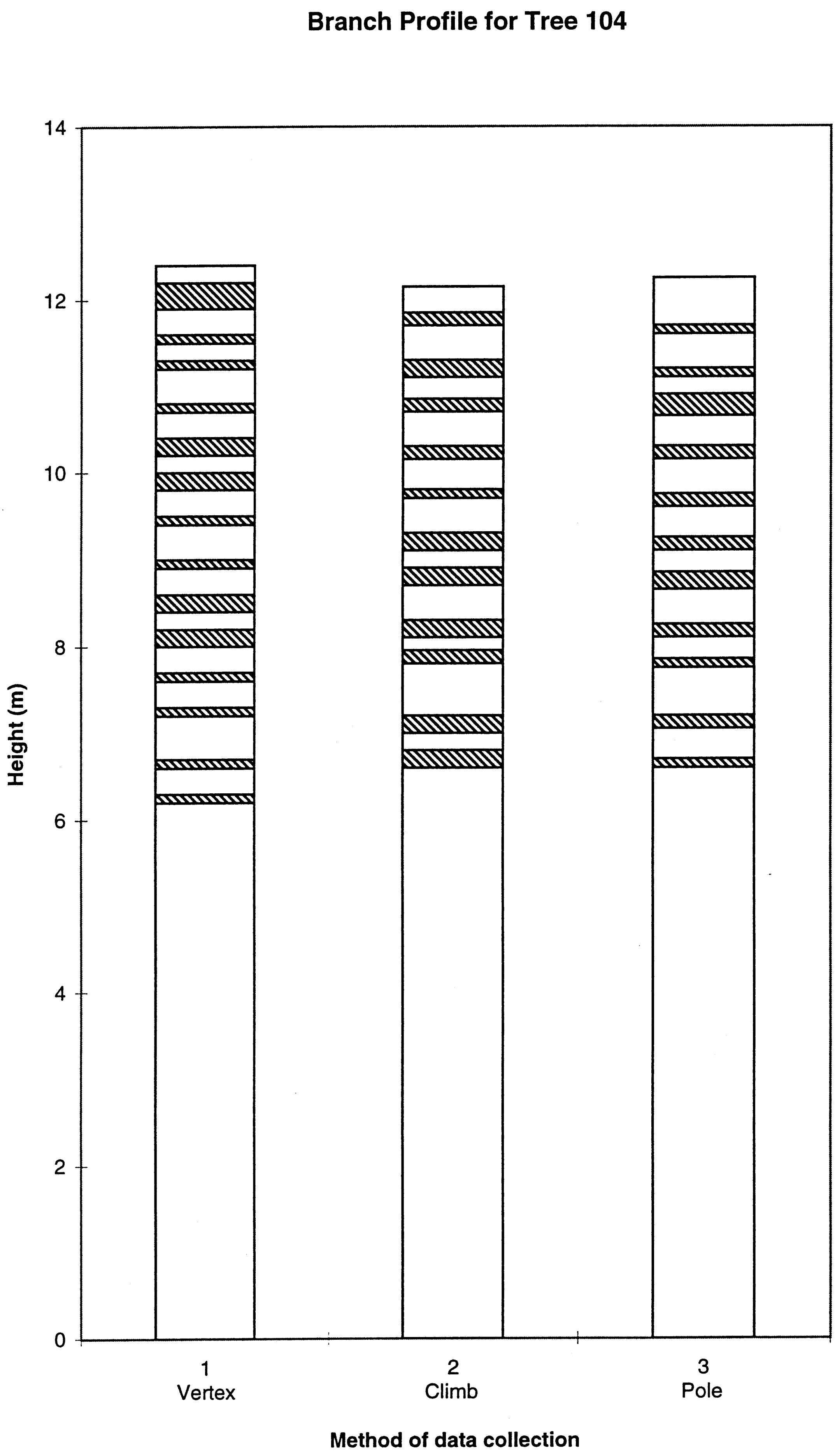


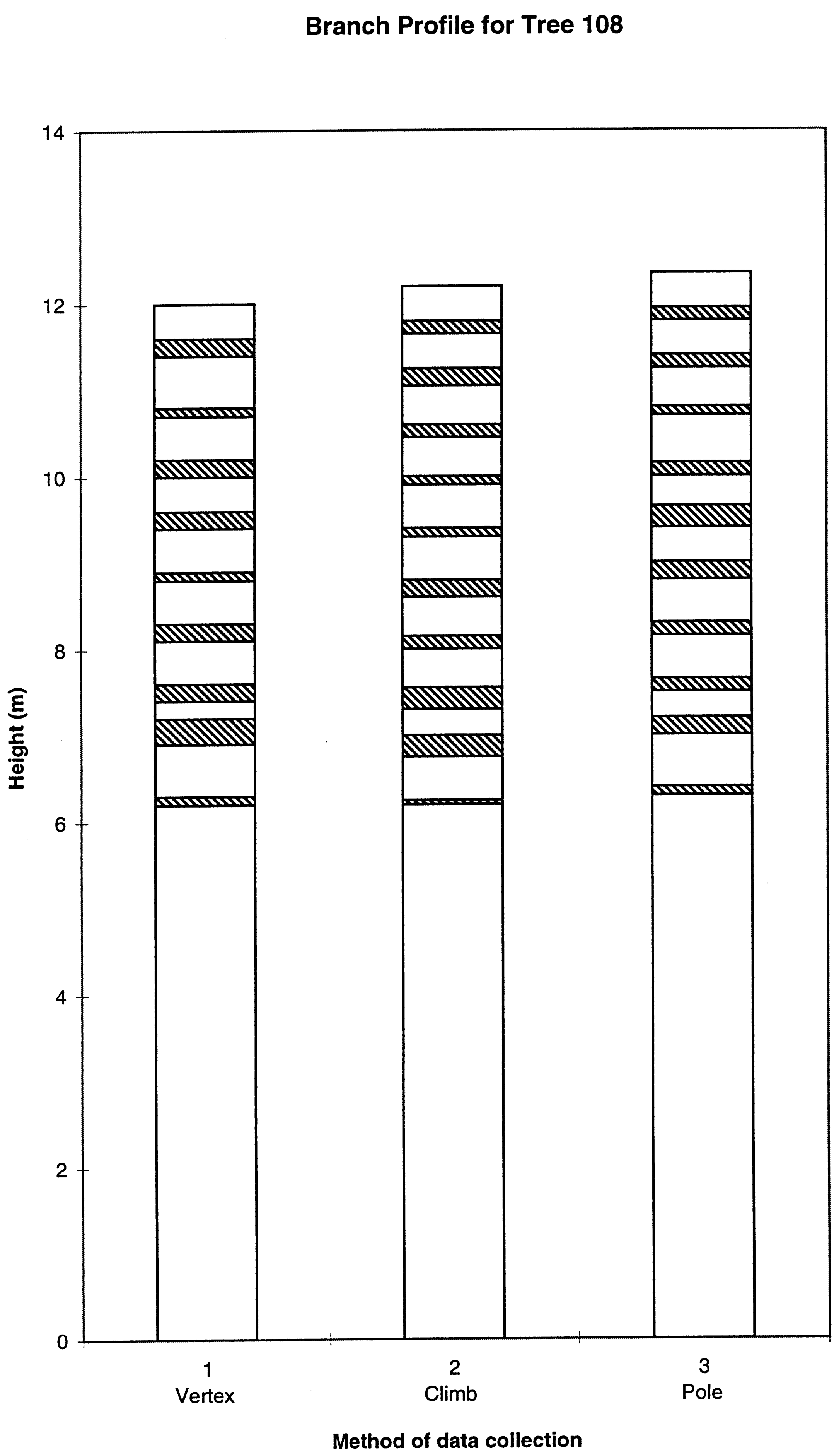

Branch Profile for Tree 65
Height (m)
14
12
10
8
6
4
2
0
1
Vertex
2
Climb
3
Pole
Method of data collection


Branch Profile for Tree 66
14
12
10
8
6
4
2
0
Height (m)
1
Vertex
2
Climb
3
Pole
Method of data collection

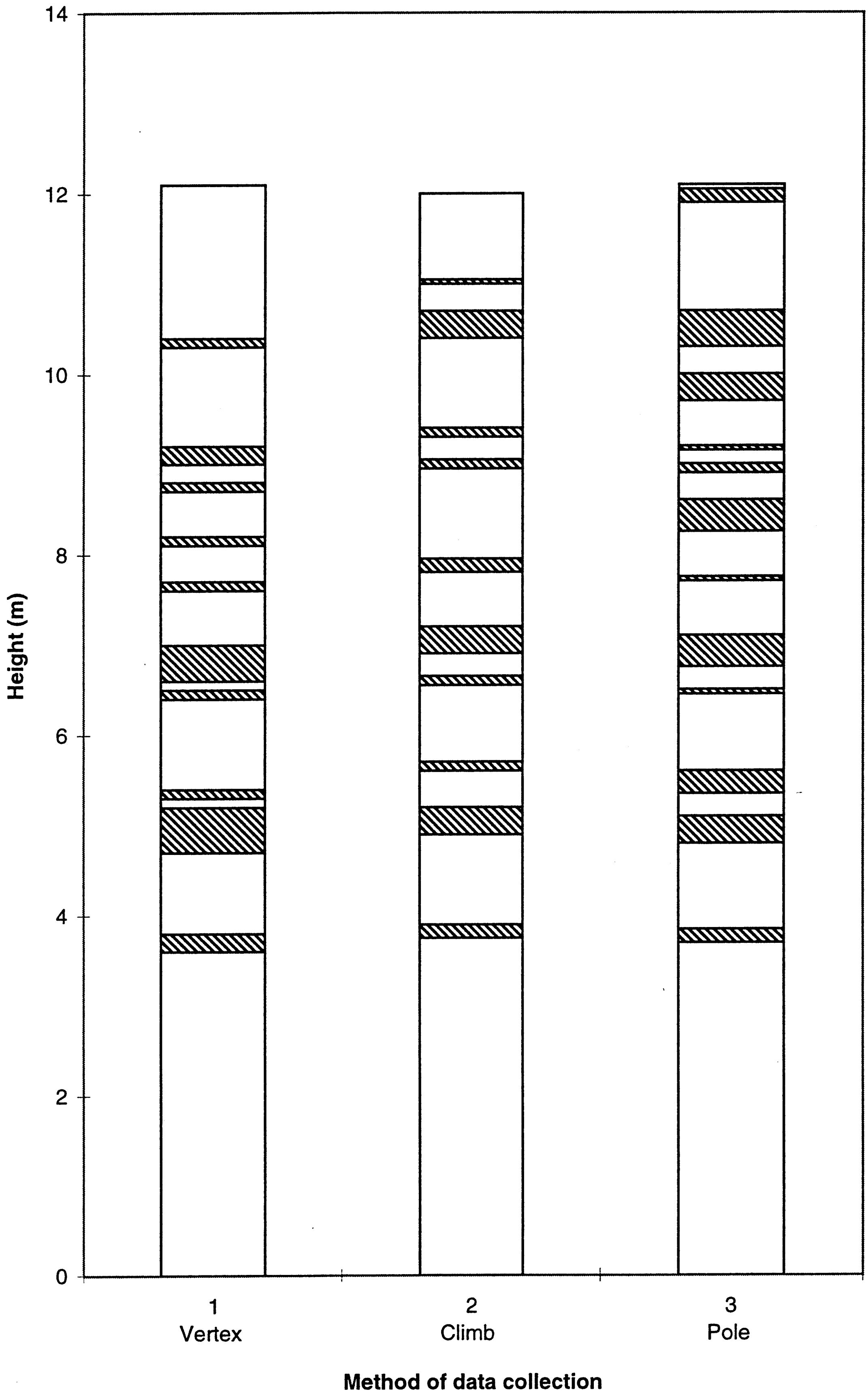


Branch Profile for Tree 79
14
12
10
8
6
4
2
0
Height (m)
1
Vertex
2
Climb
3
Pole
Method of data collection

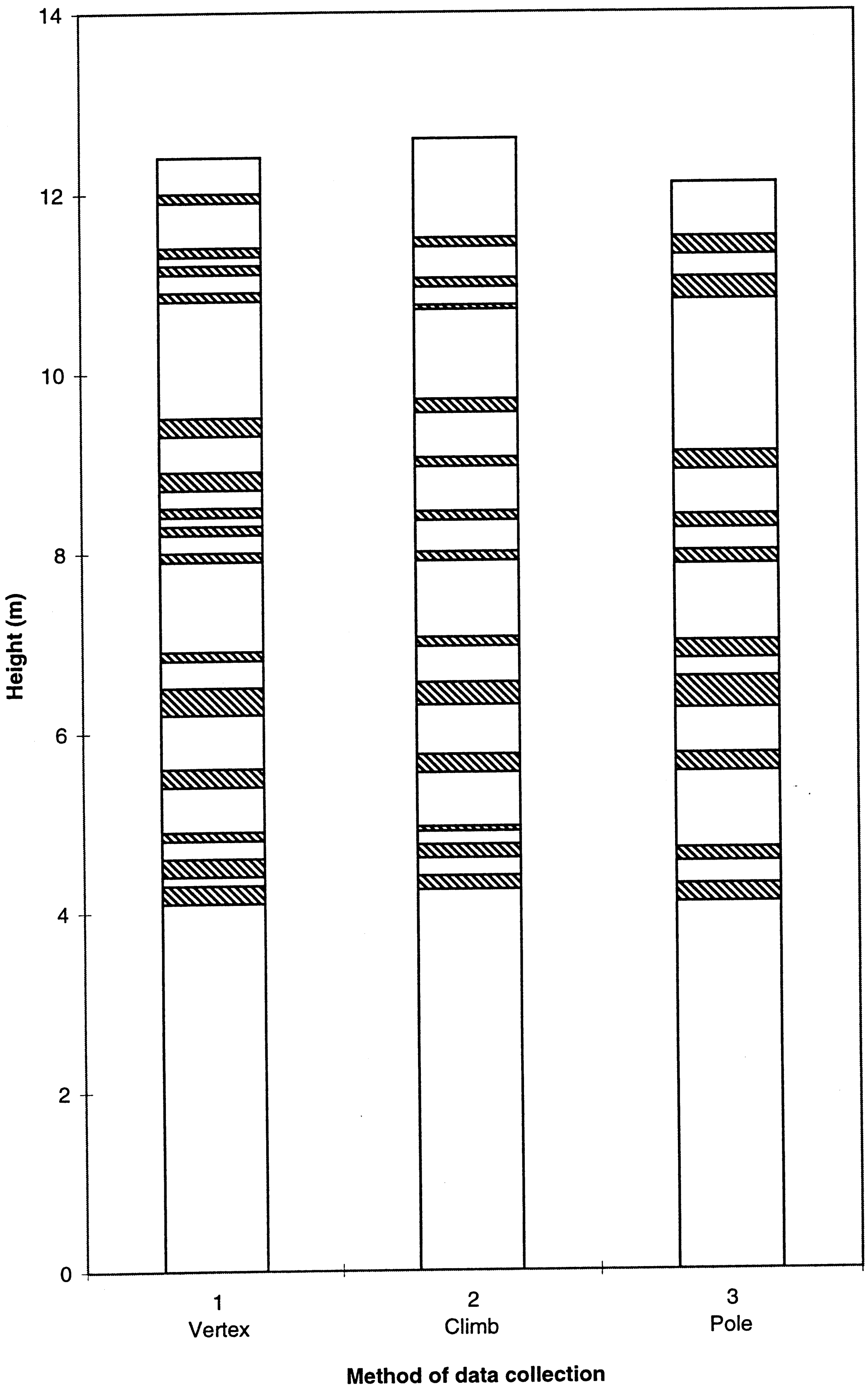

Branch Profile for Tree 104
Height (m)
14
12
10
8
6
4
2
0
1
Vertex
2
Climb
3
Pole
Method of data collection


Branch Profile for Tree 108
Height (m)
14
12
10
8
6
4
2
0
1
Vertex
2
Climb
3
Pole
Method of data collection

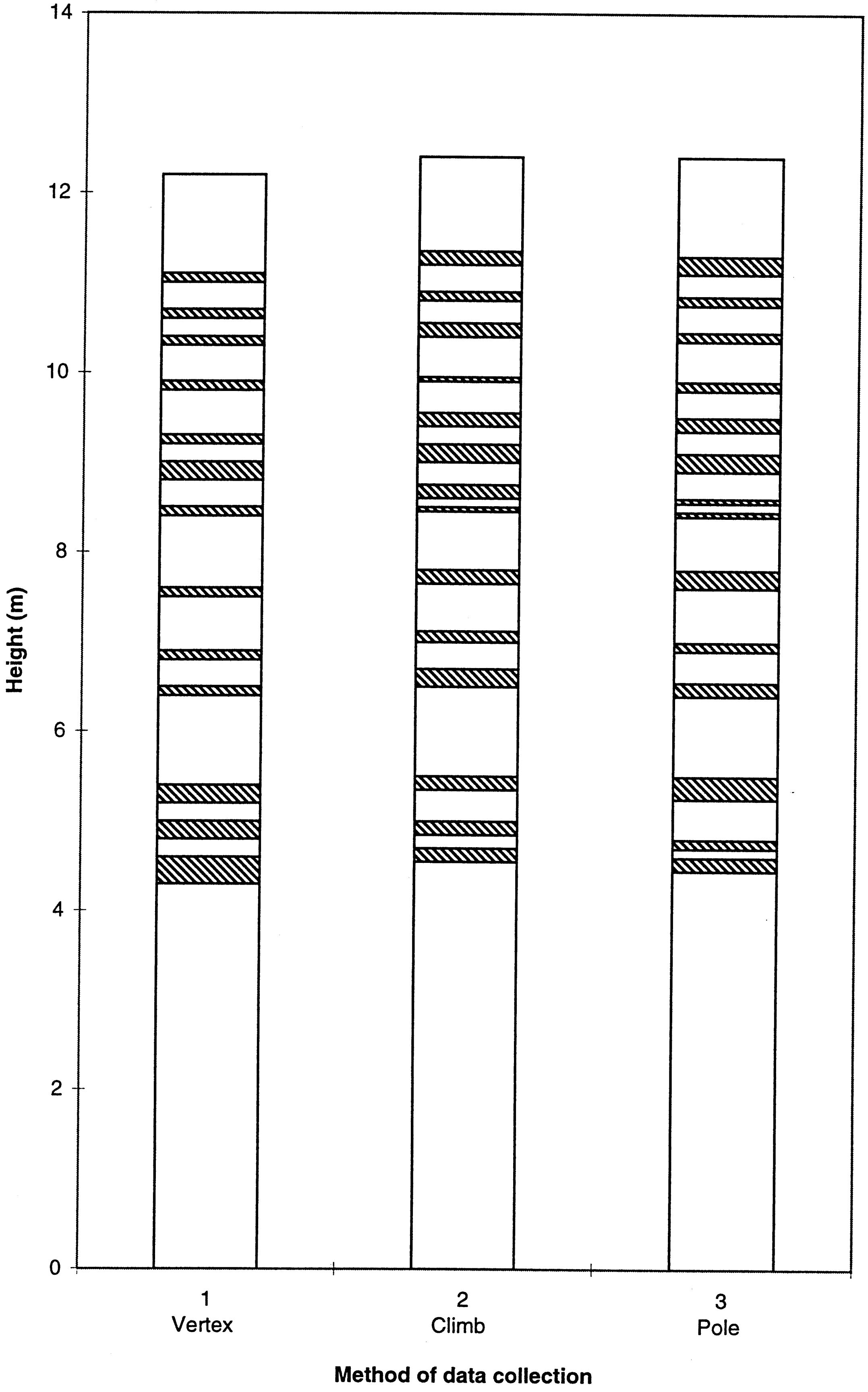
Branch Profile for Tree 109



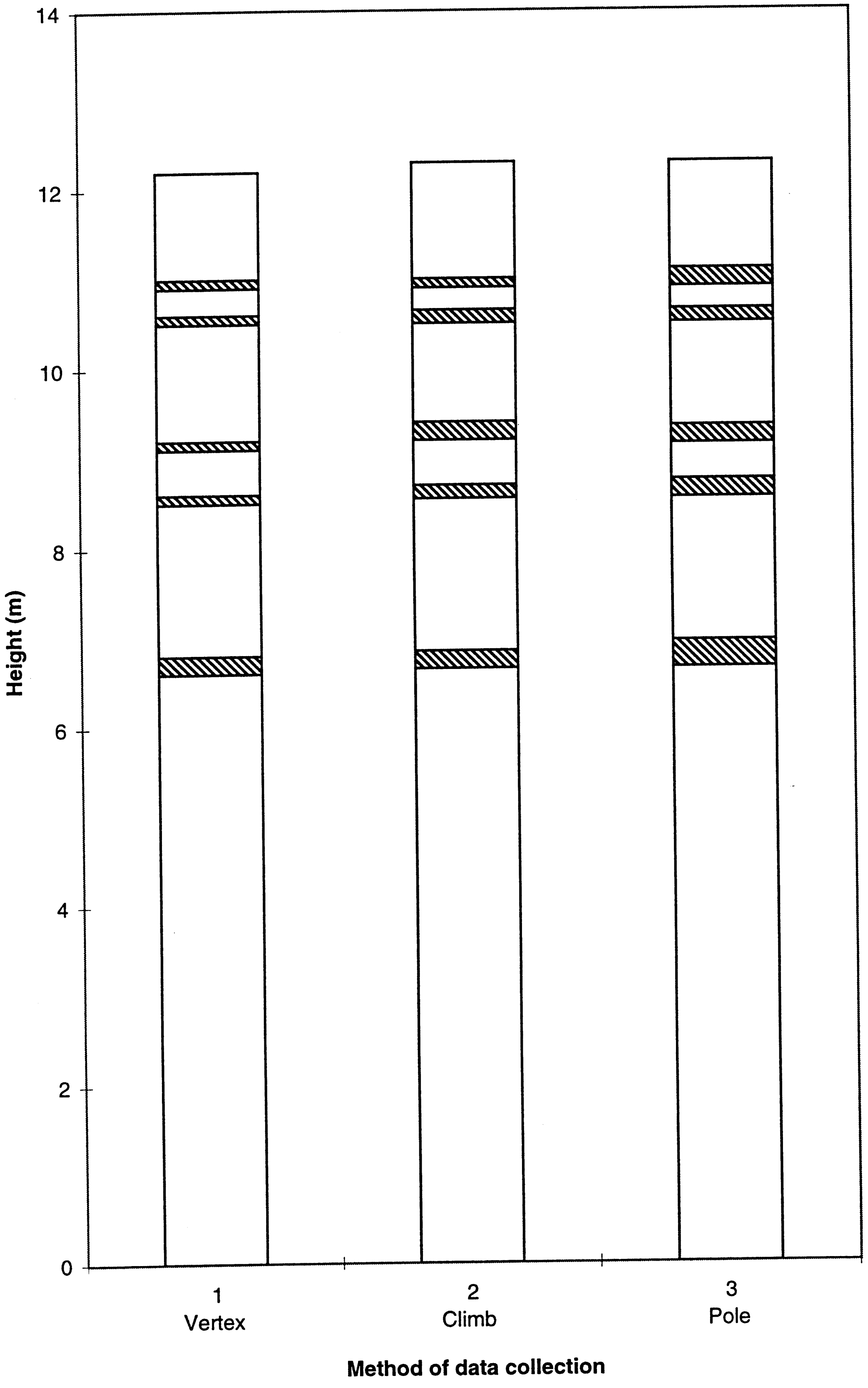
Branch Profile for Tree 114



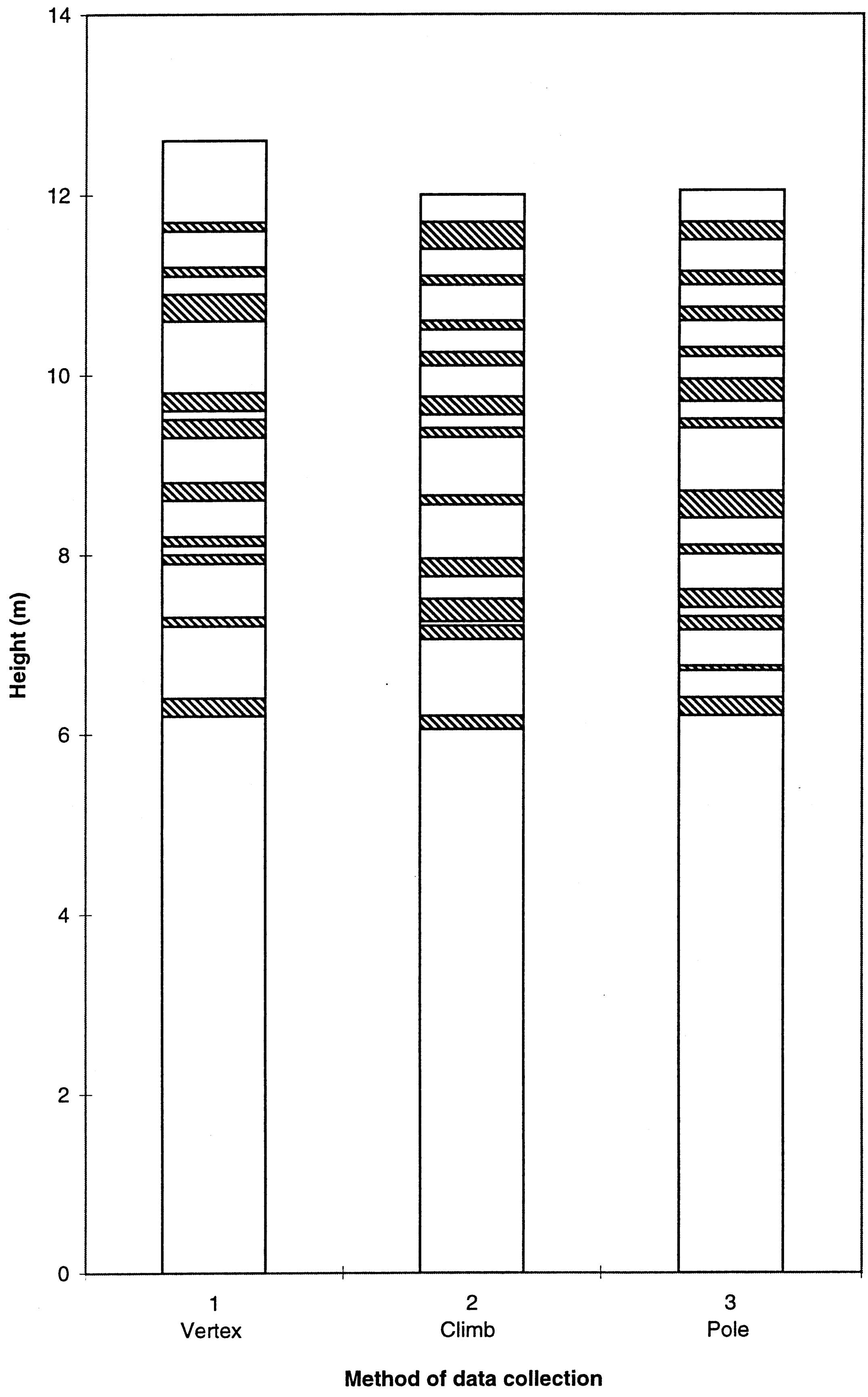
Branch Profile for Tree 118

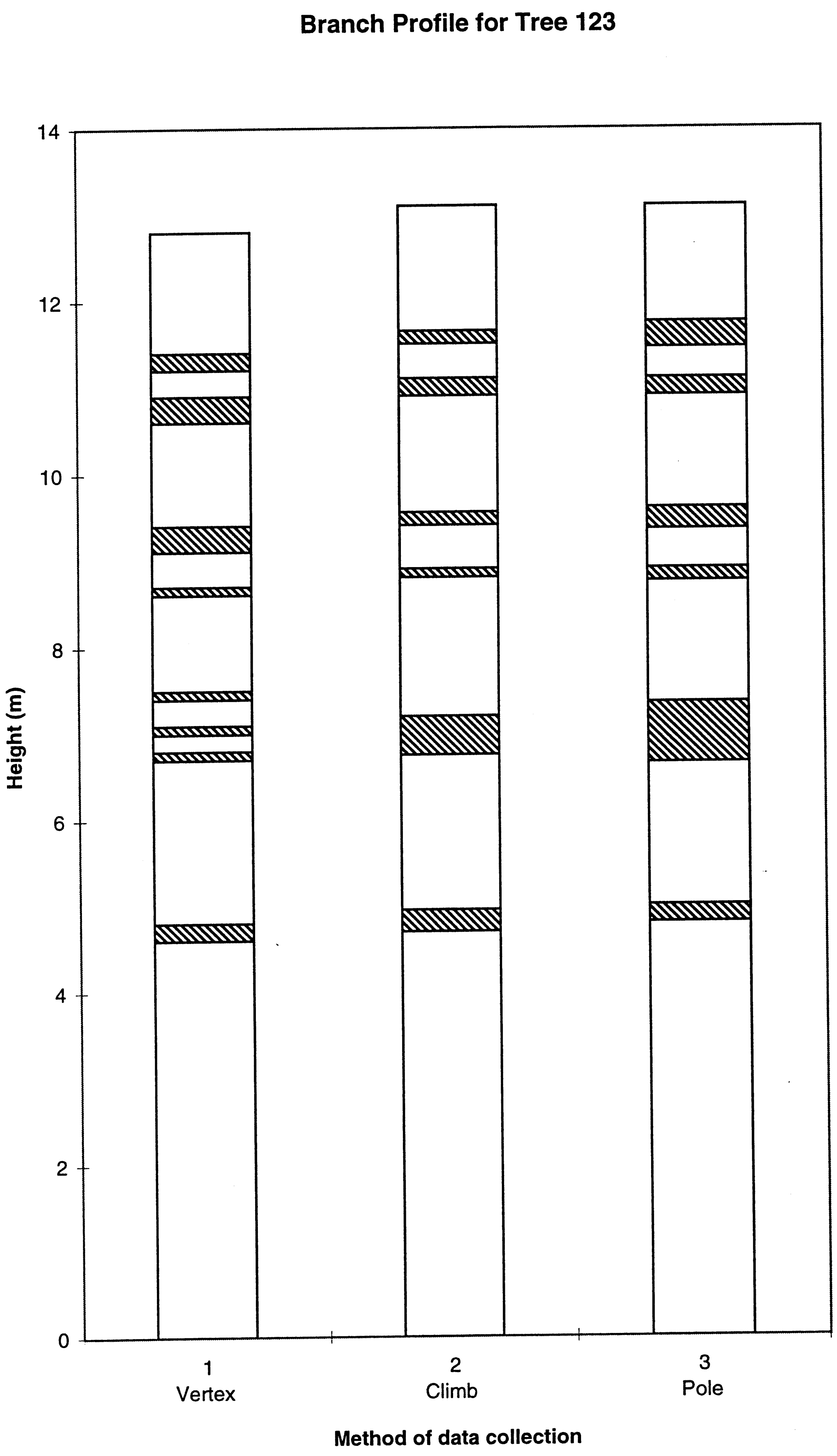


Branch Profile for Tree 119

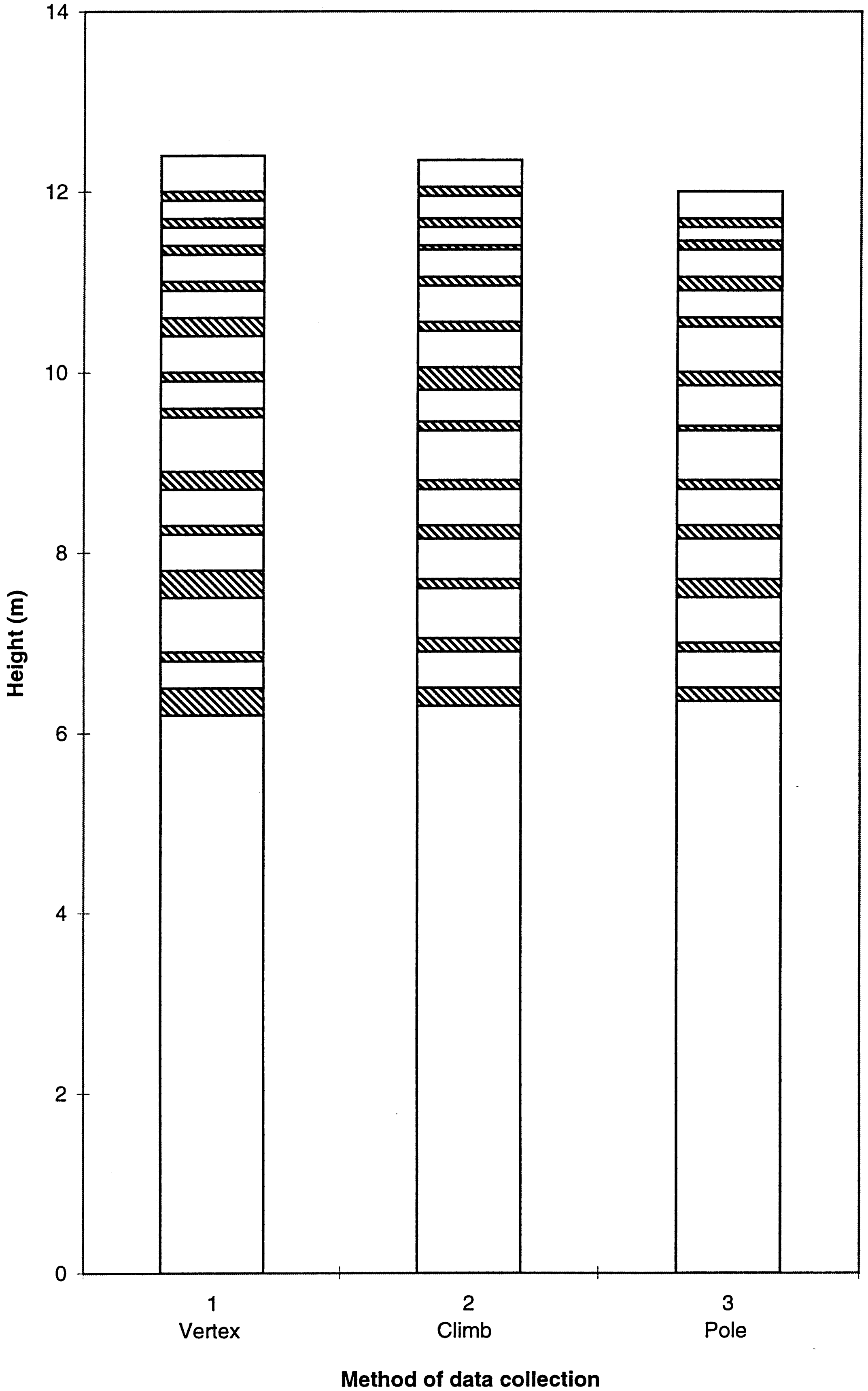


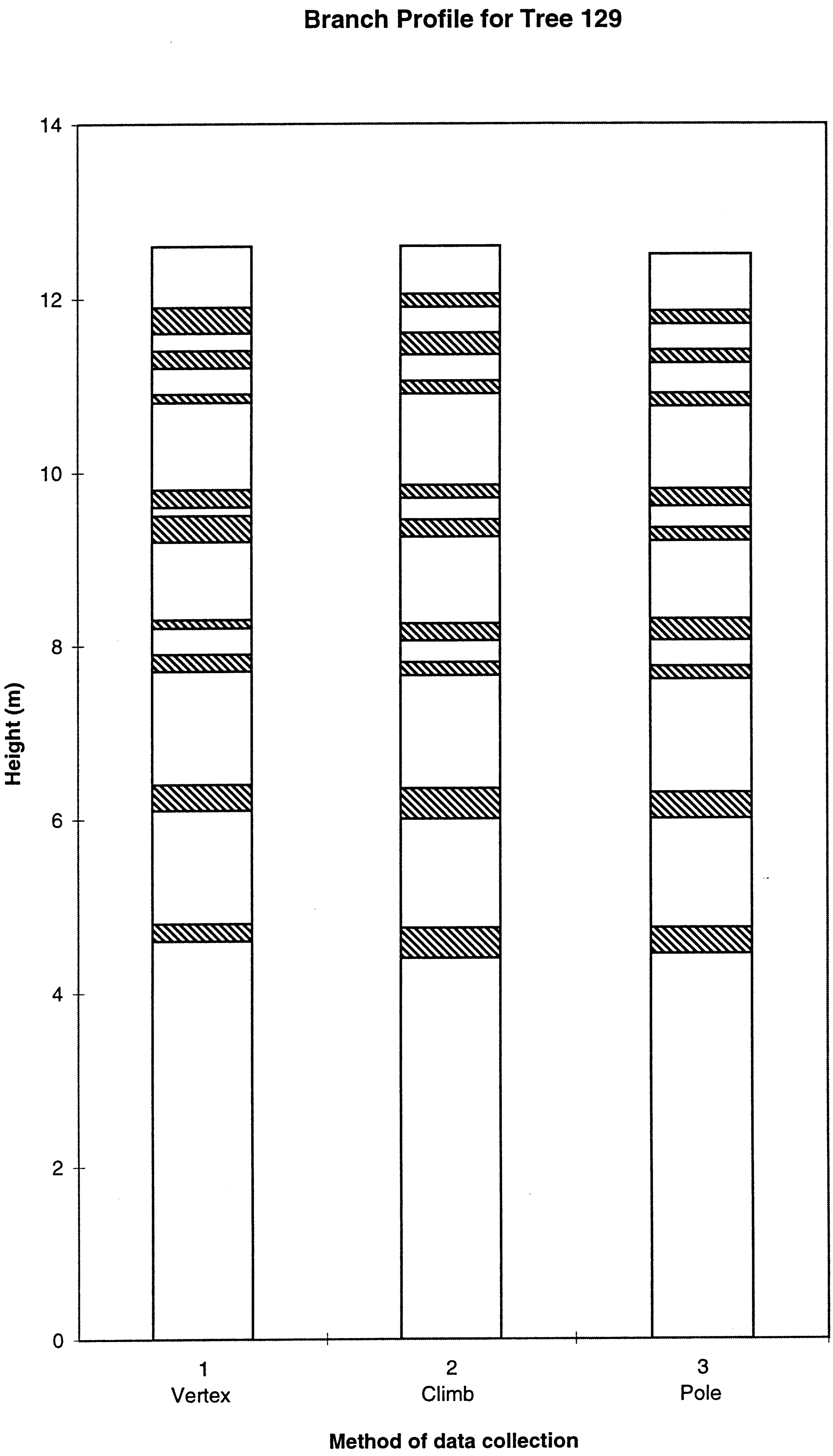
Branch Profile for Tree 121



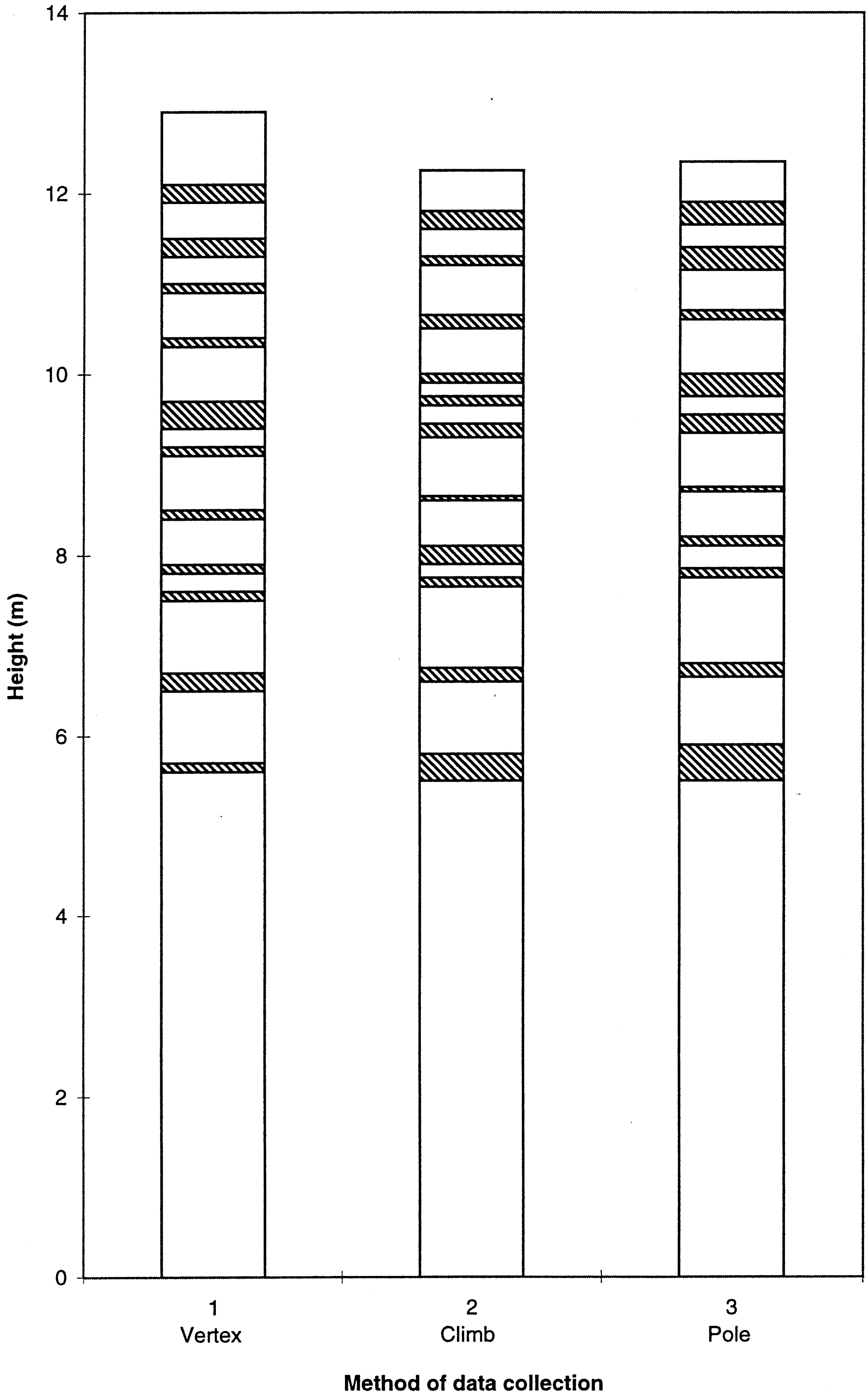

Branch Profile for Tree 123
14
12
10
8
6
4
2
0
Height (m)
1
Vertex
2
Climb
3
Pole
Method of data collection

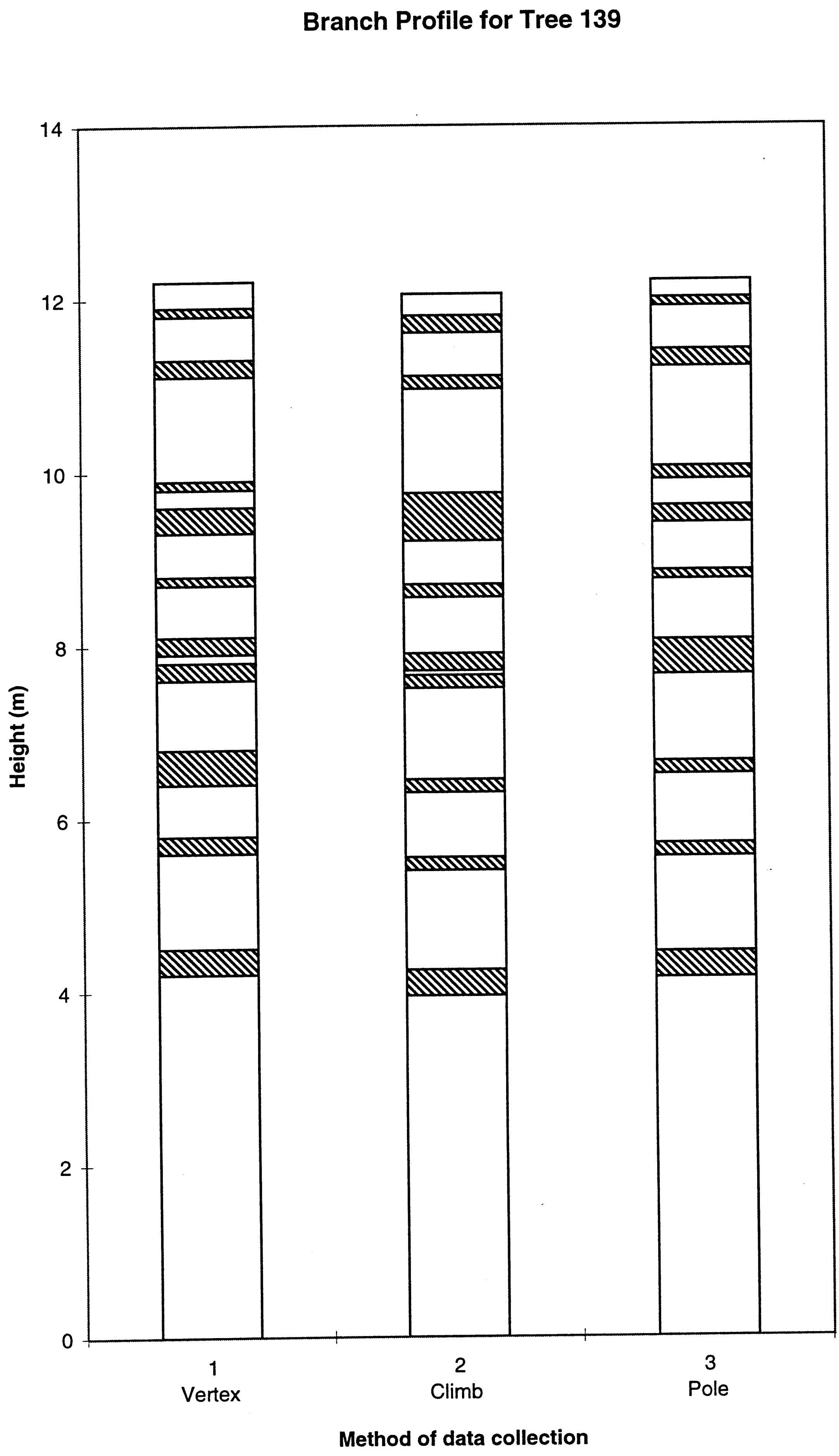
Branch Profile for Tree 125




Branch Profile for Tree 129
Height (m)
0
2
4
6
8
10
12
14
1
Vertex
2
Climb
3
Pole
Method of data collection

Branch Profile for Tree 133





Branch Profile for Tree 139
Height (m)
14
12
10
8
6
4
2
0
1
Vertex
2
Climb
3
Pole
Method of data collection

Branch Profile for Tree 141