The Development of Sampling Methods for Key-Year Patterns of White Ash (*Fraxinus americana* L.)

by

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Introduction

A key year is a year in which a significant number of trees had a wider or narrower growth ring than the previous year. A non-key year is a year in which there was not a significant number of trees that had greater or less growth than the previous year. A key-year pattern is a series of key years that are separated in time by non-key years.

The key-year pattern was introduced by Heikkenen (1980). Heikkenen developed a key-year pattern from living trees and timbers from several buildings of historical significance in Montgomery County, Virginia. Using statistical tests on each year of alignment between the key-year patterns of the living trees and the house timbers, Heikkenen was able to determine the dates in which the timbers from the houses had ceased growth.

This thesis will discuss the development of a key-year pattern, using 12 radii (samples) from each of 16 white ash (*Fraxinus americana* L.) trees. The purpose of this thesis is to research the factors that influence the "accuracy or quality" of a key-year pattern. The parameters studied are:

1) The effect of sampling from 0.3, 2.7 and 5.2 m (1, 9 and 17 ft) above ground.
2) The effect of sampling along the long or short radii

from disks with off-centered piths.

3) The effect of the interaction of heights and off-centered piths.

4) The effect of reducing the number of trees sampled.

Several researchers have studied variation in tree growth. Duff and Nolan (1953) classified variation in tree growth at each internode as vertical, diagonal and horizontal. The vertical variation in tree growth was due to increased tree height (cambial age remaining constant). The variation in the diagonal sequence was due to increasing tree height and decreasing cambial age (i.e. following the same growth ring up the tree). The variation in the horizontal sequence was due to climatic differences and the age of the tree when the growth ring was laid.

Fritts (1965), utilizing Glock's (1935) 295 year old ponderosa pine (Pinus ponderosa Laws.), which had been divided into 8 disks (cross-sections) at heights corresponding to 20-year increments, did a study of within-tree variation of ring widths. Fritts found "less agreement (1) in the uppermost portions of the stem, (2) in sections near or just below main branches, (3) at the ground line, and (4) in segments produced when rings were widest and the climatic factors most favorable." Fritts also found excellent agreement in samples taken from "the first six sections and for time periods when rings were narrow and climatic factors highly limiting". Fritts found that samples taken at breast height [1.3 m (4.25 ft)] from the ground probably provided the best estimates of variations in macroclimate.

Laar (1976) found that basal growth rings of Norway spruce (Picea abies L.) trees had greater sensitivity to annual variations in growing conditions than did growth rings from positions higher in the stem.

Fritts (1976) found that by increasing the number of trees sampled, he could reduce the standard error of the measured growth rings. He also found that increasing the number of cores per tree decreased the standard error. Fritts noted that increasing the number of trees sampled was a more effective way of error reduction than increasing the number of cores per tree; 17 trees with one core per tree were sufficient to reduce the error to 0.05 or less, whereas 12 trees with two cores per tree would be needed to obtain the same error value. Fritts concluded that the most efficient method of sampling would be to take one core from at least 17 trees, unless conditions warranted otherwise. Fritts, however preferred to take two samples from 12 trees because of the difficulty in sampling in rough terrain. Two cores per tree were also needed for some statistical tests which Fritts used.

An understanding of the variation discussed in the preceeding paragraphs may provide some assistance in determining an optimum sampling strategy. The goal of this thesis is to arrive at a conclusion as to the most efficient method of sampling white ash trees for the development of a key-year pattern. Later work may indicate that a similar approach will be useful with other species.

Methods

This study is based on a series of growth rings from samples taken along 4 radii at 3 separate tree heights of 16 white ash trees.

Study Area

The area studied was located on Crawford's Ridge in Montgomery County, Virginia; approximately 16 km (10 miles) Northeast of Blacksburg, along route 785 (Fig. 1). The study area was at an elevation of 610 m (2,000 ft), on an eastward aspect, with an average slope of 26 percent. The soils are derived from a cherty dolomitic limestone. The soil series in the study area is Rockland on the steeper slopes (> 26%) and Fredrick on the lesser slopes (< 26%). Water permeability is rapid.

Stand Decription

The stand was composed of a hardwood-pine mixture. The major tree species encountered in the study area are given in Table 1. The age of the trees sampled ranged from 61 to 197 years old with an average age of 106 years. The diameter at 0.3 m (1 ft) above ground ranged from 3.0 m to 4.6 m (12 to 18 inches) with an average diameter of 3.6 m

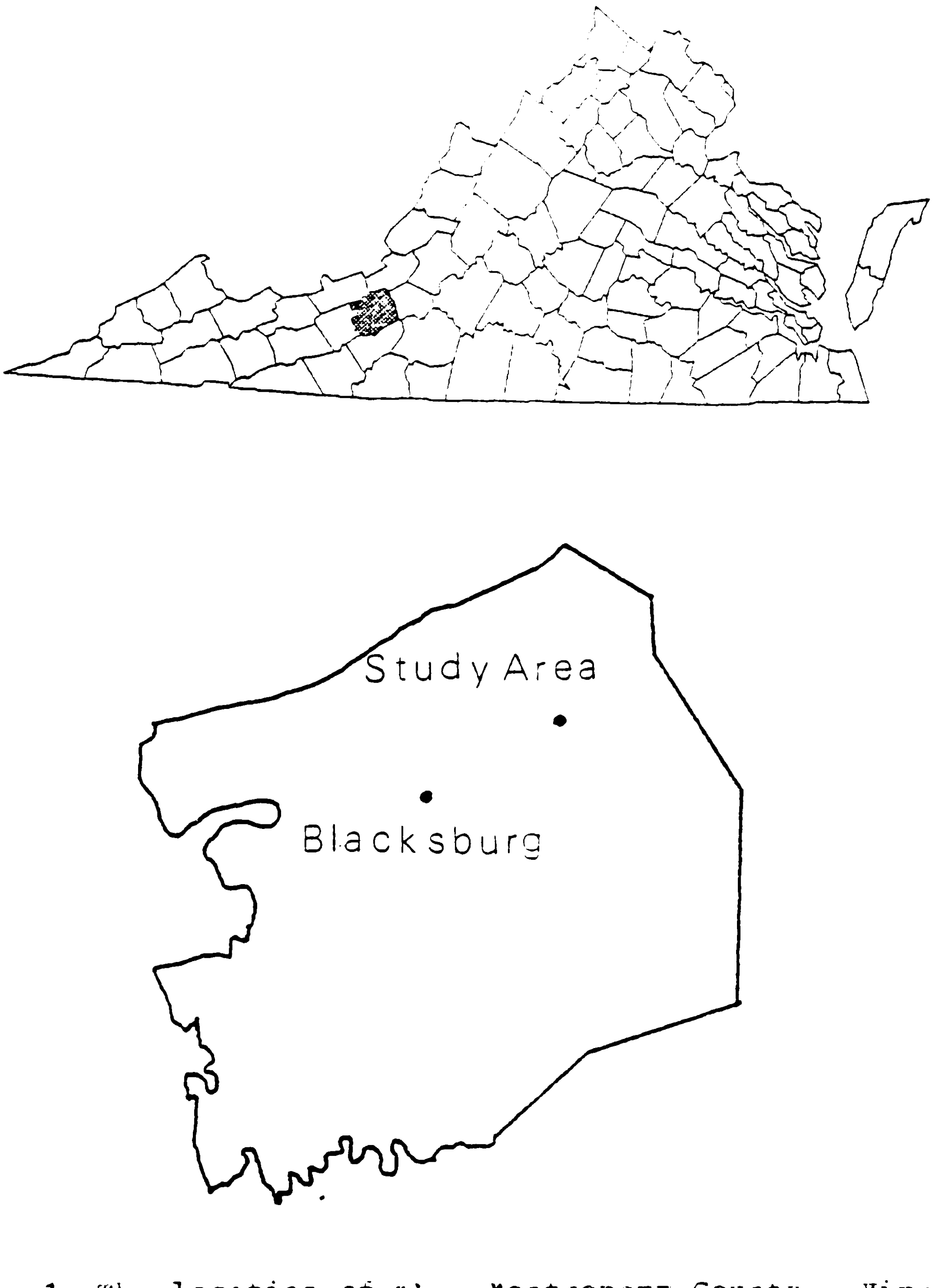

Figure 1. The location of a) Montgomery County, Virginia, and b) the approximate location on Crawford's Ridge where the study was conducted.

Table 1. The major tree species found on the study area on Crawford's Ridge, Montgomery County, Virginia.

Common Name	Scientific Name
white oak	(*Quercus alba* L.)
Northern red oak	(*Q. rubra* L.)
chestnut oak	(*Q. prinus* L.)
scarlet oak	(*Q. coccinea* Muenchh.)
white ash	(*Fraxinus americana* L.)
yellow poplar	(*Liriodendron tulipifera* L.)
hickory	(*Carya* spp.)
sugar maple	(*Acer saccharum* March.)
black walnut	(*Juglans nigra* L.)
Virginia pine	(*Pinus virginiana*)
shortleaf pine	(*P. echinata* Mill.)

(15 inches).

Species Selection

This study was confined to white ash because of the characteristics of the wood. The growth rings are distinct (wood ring-porous) and the early-wood pores are large in comparison to the late-wood cells. The rays are not distinct and cause no apparent distortion tc the growth rings (Panshin and Zeeuw 1964).

Sample Preparation

A disk was chain-sawed from the bottom of each 2.4 m (8 ft) log from tree lengths that had been skidded to a landing. This provided a representative sample from 3 heights above ground from each of 16 trees (Fig. 2). The disks were sawn at 0.3, 2.7, and 5.2 m (1, 9, and 17 ft) above ground. The samples were obtained between August 25 and September 5, 1977.

Four radii were sawn from each disk (Fig. 3). Each radius was then smoothed with a belt-sander using increasingly finer sand-paper until the growth rings could be readily distinguished.

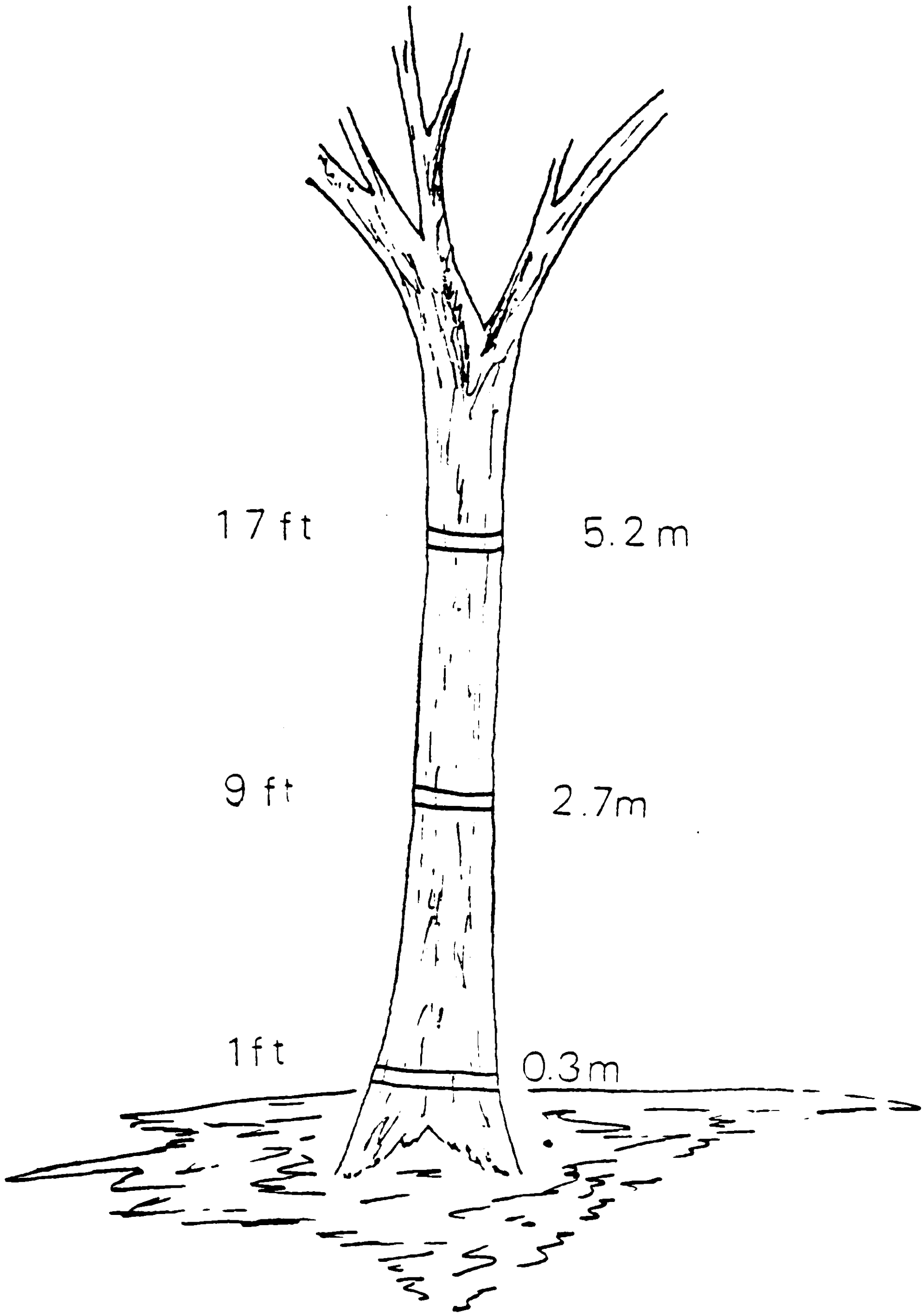

Figure 2. The location of the lower, middle and upper disks sampled from each tree.

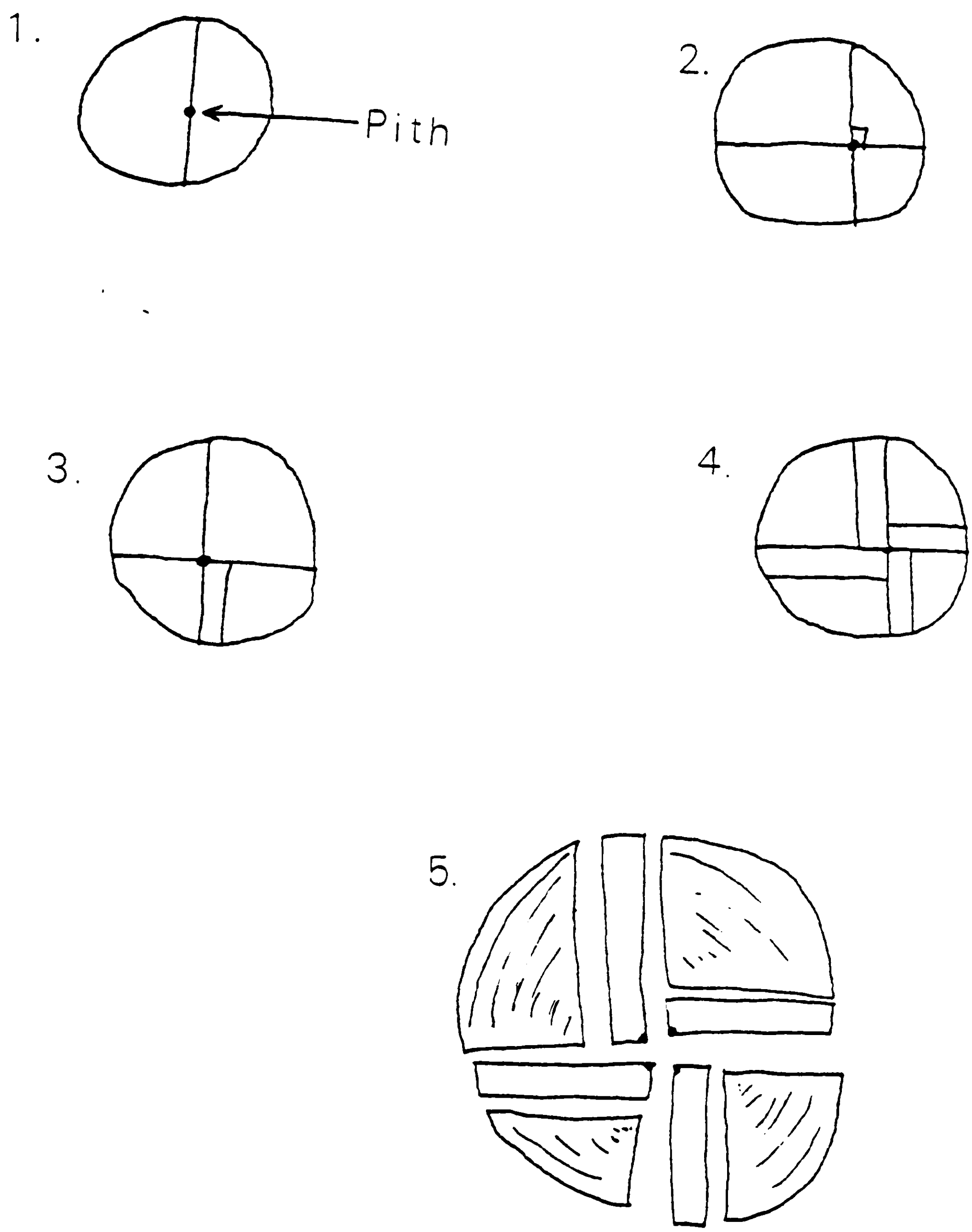

Figure 3. A diagram showing the procedure used to cut 4 radii with a common pith from each disk sampled.

Growth Ring Measurements

The growth rings of each radius were measured to the nearest 0.01 mm on a dendrochronometer. The measurements were entered into the computer for analysis.

The first 10 years of annual growth (nearest the pith) were not used in this analysis. The first growth rings formed on a tree do not accurately reflect the climatic conditions as well as the growth rings formed later in the life of the tree. Forward and Noland (1961) found that open-grown pine trees had consistently wide growth rings for a maximum of 9 years before they began fluctuating in growth from year-to-year.

Relative Ring Widths

A given ring width was transformed into a relative ring width, using the technique described by Heikkenen (1980) and Ferguson (1979). A relative ring width was assigned to a given year depending upon it being greater than (+), less than (-) or equal (0) to the previous growth ring. It was assumed that each year had an equal chance of being a + or a - relative ring width. However, in order to justify later statistical methods the probability of a relative ring width occurring had to be tested. Therefore, the following procedure was used to test if the occurrence of a + and a -

relative ring width was statistically equal (Hollander and Wolfe 1973).

Test:

H_o: p=0.5, a + and a - relative ring width have an equal chance of occurrence or

H_a: p=0.5, a + and a - relative ring width do not have an equal chance of occurrence.

Where:

p^- = probability of success (a - relative ring width),

p_o^- = hypothesized probability (0.5),

α = set at 0.05 (95%) confidence,

n= sample size (total observed + and - relative ring widths= 11,208),

B= number of successes identified (number of observed - relative ring widths= 5,632),

B*= large sample approximate normal statistic, and

$Z(\alpha)$ = the upper percentile of the normal N(0,1) distribution (1.96).

Then:

reject: H_a if $B^* \geq 1.96$ or

accept: H_o if $B^* < 1.96$.

When:

$B^*=(B-Np_o^-)/[np_o^-(1-p_o^-)]$;

$B * (5632-11208*0.5)/[11208*0.5(1-0.5)]=0.5290.$

Thus:

Since B* < 1.96, H_a:p=0.5 is rejected in favor of H_0:p=0.5. The minimum rejection level for B* = 0.5290 is 0.5488 which stronly supports the hypothesis p=0.5. The assumption that there was an equal chance of occurrence of a + or a - relative ring width was strongly supported. The 0 relative ring widths represented less than 2 percent of the data, therefore were not included in statistical analyses.

White Ash Key-Year Pattern

The white ash key year pattern was based on 4 radii from 3 separate tree heights of 16 trees. A year in which a significant percentage of relative ring widths ccincided was termed a key year. The statistically significant years were calculated using the upper tail probabilities of the cumulative binomial distribution. The occurrence of a series of statistically significant years was termed the white ash "key-year pattern". The white ash key-year pattern was used as a standard to measure the influence of sampling from different tree heights and frcm off-centered piths.

Factors Influencing a Key-Year Pattern

The "accuracy" or "quality" of a key-year pattern may be influenced by the height above ground as well as by off-centered piths. The literature indicated reduced reliability with increased tree height (Fritts 1965, Laar 1976). If the assumption is valid, the variation in the measured growth ring caused by tree height and off-centered piths would increase the probability of error involved in developing a key-year pattern. As the probability of error increased, the number of trees needed to establish a key-year pattern would increase.

Tree Height

The procedure used to identify the tree height with the highest agreement involved comparing 4 radii at 3 heights against the white ash key-year pattern. More specifically, if 3 out of the 4 radii for a given year and height had identical relative ring widths, that year was classified as a key year for the tree. Three key-year patterns were constructed for each tree, representing each height.

Once a key-year pattern for a given tree and height was established, it was compared to the white ash key-year pattern. A 3 by 3 contingency table was used to tally agreements and disagreements between the white ash key-year pattern and all trees at specific heights. In every instance where a key year for a given tree at a specific height coincided with a key-year in the white ash key-year pattern, an entry was made along the diagonal of the contingency table. Disagreements were tallied on the off-diagonals.

The probability of each value in the contingency table occurring was estimated by its proportion of the total observed values. This formed the contingency table of probabilities.

The test for agreement (Bishop, et al. 1974) utilized these contingency tables to measure the degree of agreement between the tree height and the white ash key-year pattern. The following formulae were used to measure the degree of agreement ($\hat{K}$) and the variance ($\sigma^2_\infty[\hat{K}]$) about kappa ($\hat{K}$) for each height.

Solve:

$$\hat{K} = (N \sum_{i=1}^{I} X_{ii} - X_{i+} + X_{+i}) / (N - (\sum X_{i+} + X_{+i}))$$

$$\sigma^2_\infty [\hat{K}] = (1/N)[((\theta_2(1-\theta_2))/(1-\theta_2)^2) + ((2(1-\theta_2)(2\theta_1\theta_2-\theta_3)))/(1-\theta_2)^3) + (((1-\theta_1)^2(\theta_4-4\theta_2^2))/(1-\theta_2)^4)]$$

Where:

$$\theta_3 = \sum P_{ii}(P_{i+} + P_{+i}),$$

$\theta_4 = \Sigma p_{ij} \ (p_{j+} + p_{+i})^2$,

$\hat{K}$= (kappa statistic) the average degree of agreement,

N= the total number of tree rings measured and used in this analysis,

X_{ii} =observed values that are in agreement (the values along the diagonal of the contingency table),

p_{ii} = the values along the diagonal of the contingency table of probabilities,

$(X_{i+} + X_{+i})$= the sum of row i and column i of the contingency table of observed values,

$(P_{i+} + P_{+i})$= the sum of row i and column i of the contingency table of probabilities,

$\sigma^2_{\infty}[\hat{K}]$= the approximate large sample variance of kappa

θ_1= the sum of the diagonals of the contingency table of probabilities,

θ_2= sum of the products of the off-diagonals (i.e. the product of row 2 column 1 and row 1 column 2), and

P = proportion of the total observed values in which N occurs (the estimated probability cf an observed value occurring).

The 3 kappa statistics (one for each height) were tested for significant differences, using Duncan's multiple range test

(Miller 1966).

Off-Centered Pith

The procedure for identifying the radial length with the highest agreement was similar to that used with the heights. The radii at each tree height were designated as long, medium long, medium short and short, dependent on their relative lengths (Fig. 4). The long, medium-long, medium-short and short radii had an average length of 12.52, 10.33, 8.85 and 7.85 cm (4.93, 4.07, 3.09 and 3.48 inches), respectively. All of the long, medium-long, medium-short and short radii were considered as 4 separate radial-length groups. A radial-length group consisted of one sample from each height of each tree.

Out of 192 radii, 10 were missing (due to defects in the wood, i.e. scars), and were placed in the medium-short category. This action was determined not to effect results because the categories used remained relatively longer or shorter in length. For example, if the missing radius should have belonged to the long radial-length group instead of to the medium-short group, it would not affect results because the remaining radii would still be relatively shorter or longer than the other groups. The goal was merely to show which category expressed the highest and

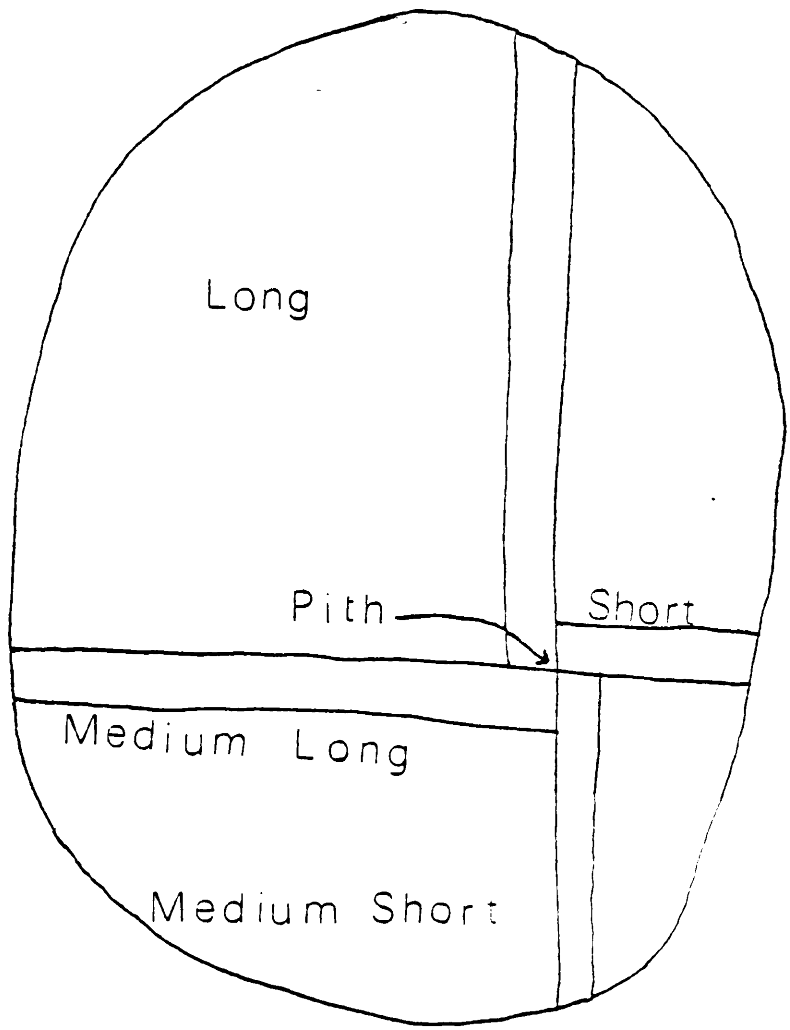

Figure 4. A diagram designating the long, medium-long, medium-short and short radius lengths.

lowest agreement with the white ash key-year pattern. Because of the reduced number of samples, the medium-short radial-length group was not used in the final analysis.

Three key-year patterns were constructed using the relative ring widths of these radial-length groups. The relative ring widths of the radii from each of the 3 heights had to agree in order for a given year to be classified as a key year. Three contingency tables were used to tally the agreements and disagreements between the radial-length groups and the white ash key-year pattern. Three contingency tables were also used to present the probability of occurrence of the observed agreements and disagreements.

The level of agreement ($\hat{K}$) and the variance ($\sigma^2_\infty[\hat{K}]$) were determined for each radial-length group using the test for agreement (Bishop et al. 1975). Significant differences in the level of agreement between the long, medium-long and the short radial-length key-year patterns were tested using Duncan's multiple range test.

<u>Interactions of Tree Heights and Off-Centered Piths</u>

Once the key-year patterns of the various heights and radial-length groups were tested for agreement with the white ash key-year pattern, radii from the height and radial-length group with the highest and lowest agreement were used to develop 2 key-year patterns. One key-year pattern was developed using radii from the height and radial-length group with the highest agreement to represent the best extreme in sampling. Another key-year pattern was developed using radii from the height and radial-length group with the lowest agreement to represent the poorest extreme in sampling. These extremes represented the variation in sampling that could occur.

The upper tail probabilities of the cumulative binomial distribution (α=0.05, p=.5) were used as the criterion for determination of key years. Two contingency tables were used to tally the observed agreements and disagreements between the white ash key-year pattern and the key-year patterns of the two extremes. Two contingency tables were also used to present the probability of the observed agreements and disagreements occurring. The key-year patterns of these extremes were tested for agreement against the white ash key-year pattern.

Sample Size

Agreement was tested using successively smaller sample sizes between 16 and 8 trees. More specifically, for a sample size of 15, a single tree was dropped and the degree of agreement between 15 trees and the white ash key-year pattern was calculated. In a similar fashion every possible combination was made of the 16 trees, using 15 at a time (16 combinations). The key-year pattern for each combination of samples was used to derive the degree of agreement between that combination and the white ash key-year pattern.

Each sample size between 16 and 8 was represented by every possible combination of 16 trees and the respective agreement values. The mean and standard deviation of the agreement values was calculated for each sample size. From this information, a qualitative decision can be made regarding the sample size required under different circumstances. Having used the extremes of height and radial lengths, it may be assumed that a random selection from 16 to 8 trees would result in some degree of agreement between the two extremes.

Results

This thesis describes the establishment of a white ash key-year pattern and the influence of tree heights, off-centered piths, the interaction of different tree heights and off-centered piths and the number of trees sampled. These factors were tested in a systematic fashion to determine which sampling method had the highest agreement with the white ash key-year pattern.

The lower heights were found to have the highest agreement with the white ash key-year pattern, though not significantly higher. The long radii from off-centered piths had the highest significant agreement with the white ash key-year pattern. The long radii at lower tree heights had twice the amount of agreement with the white ash key-year pattern as did the short radii from upper tree heights. Eight samples of long radii at lower tree heights were shown to have adequate agreement with the white ash key-year pattern. Twelve trees using short radii at upper heights would be needed to maintain the same amount of agreement as was acheived using 8 samples of long radii at lower heights.

White Ash Key-Year Pattern

The white ash key-year pattern was constructed using all radii from all trees. The upper tail probabilities of the cumulative binomial distribution ($p=0.5, \alpha=0.1$) was used as a criterion for the key year determination. Sixty-three of the 75 years were found to be key years (Appendix A).

The number of trees representing a given year ranged from a maximum of 182 in 1976 to a minumum of 79 in 1902. The reduction of samples in any given year did not effect the results because it effected all radii similarly. The reduction of samples in a given year changed the criterion for a key year from 55 percent agreement in 1976 to 58 percent in 1902.

Factors Influencing a Key-Year Pattern

The white ash key-year pattern was treated as the standard tree growth because of the large number of radii used to compile it (182 radii). The white ash key-year pattern was considered as a standard to be compared with key-year patterns that were developed from samples from specific heights and radial lengths.

Tree Heights

Key-year patterns composed of samples from upper-tree heights had a decreasing amount of agreement with the white ash key-year pattern. However, there was no significant difference in the level of agreement found among the various tree heights. The following procedure was used to determine which tree height had the highest agreement.

An agreement of 3 of the 4 relative ring widths for a given year at a specific height was used as the criterion for a key year. The key years for each tree from the upper, middle and the lower heights were established (Appendices B, C and D, respectively).

Three contingency tables were used to present the agreements and disagreements between the 3 heights of each tree and the white ash key-year pattern (Appendix E). Strong agreement was indicated by the relatively high values along the diagonal of the contingency tables (cells 1,1, 2,2 and 3,3). Disagreement is represented by off-diagonal values (cells 1,2, 1,3, 2,1, 2,3, 3,1 and 3,2). The three contingency tables were used to display the probability of the observed agreements and disagreements (Appendix F).

The test for agreement utilized the contingency tables to determine which height had the highest agreement with the white ash key-year pattern. The kappa statistic, variance of kappa, standard deviation of kappa and the standard normal kappa for each tree height (Table 2) was derived from the agreements and disagreements tallied in Appendix E. These statistics indicated decreasing agreement with

Table 2. The kappa statistic, variance of kappa, standard deviation of kappa, and the standard normal kappa for the lower, middle, and upper tree height key-year patterns.

Statistic	Tree Height		
	Lower	Middle	Upper
Kappa	0.309	0.300	0.245
Variance	0.000581	0.000608	0.000685
Standard Deviation	0.0241	0.0247	0.0261
Standard Normal	12.826	12.165	9.359

increasing tree height; however no significant differences (α=0.05) were found between the three kappa statistics, based on Duncan's multiple range test. Therefore, sampling from tree heights of 0.3, 2.7 and 5.2 m was determined not to be a critical factor in the construction of the white ash key-year pattern.

Off-Centered Pith

Key-year patterns developed from long radii were found to have statistically higher agreement with the white ash key-year pattern than key-year patterns developed from radii of shorter lengths. The following procedures were used to determine which radial-length key-year pattern had the highest agreement with the white ash key-year pattern.

Agreement of all three of the relative ring widths for each year was used as a criterion for identifying a key year. The key years for each tree were identified as the long, medium-long and short radial-length group (Appendices G, H and I, respectively).

Three contingency tables were used to tally agreements and disagreements between each radial-length group and the white ash key-year pattern (Appendix J). Strong agreement was indicated by high values along the diagonal of the contingency tables. Disagreement was indicated by values on the off-diagonals. Three contingency tables were constructed to present the probability of occurrence of the observed agreements and disagreements (Appendix K).

The test for agreement utilized these contingency tables to compute the kappa statistic, variance, standard deviation and standard normal kappa for each radial-length group (Table 3). These statistics indicated increasing agreement with increasing radial length. The long radial lengths had the highest agreement.

Duncan's multiple range test indicated a significant difference ($\alpha=0.05$) between the long radial-length group and the other two groups. No significant difference was found between the medium long and the short radial-length group. Therefore, sampling along the long radius was determined to be a critical factor in the construction of a key-year pattern.

Interaction of Tree Heights and Off-Centered Piths

The test for agreement indicated higher agreement between the white ash key-year pattern and key-year patterns developed from radii from lower tree heights and shorter radial lengths. Lower agreement was found in key-year patterns developed from radii at upper tree heights along shorter radial lengths. The long radial lengths at lower

Table 3. The kappa statistic, variance of kappa, standard deviation of kappa, and the standard normal kappa for the long, medium-long, and short radial-length key-year patterns.

Statistic	Radial Length		
	Long	Medium-Long	Short
Kappa	0.380	0.298	0.253
Variance	0.000534	0.000593	0.000649
Standard Deviation	0.0231	0.0243	0.0255
Standard Normal	16.432	12.225	9.934

heights represent the combination of tree heights and radial lengths with the highest agreement with the white ash key-year pattern. The short radial lenghts at upper tree heigths represent the combination of sample locations with the lowest agreement with the white ash key-year pattern. These results were based on the following procedures.

One sample was taken from each of the sixteen trees at lower tree heigths and along the long radial lengths. A second sample was taken from each of the sixteen trees at upper tree heigths and along short radial lengths.

The upper tail cumulative binomial distribution ($p=0.5$, $\alpha=0.1$) and the relative ring widths were used to construct key-year patterns for the two extremes in sampling (Appendices L and M). Contingency tables were used to tally agreements and disagreements between the white ash key-year pattern and the two extremes (Appendix N). Contingency tables were also used to present the probability of the observed agreements and disagreements occurring (Appendix O).

Agreement was tested between the white ash key-year pattern and the key-year patterns of the two extremes. The key-year pattern developed from the long radial lengths at lower tree heights had an agreement value of 5.17. The key-year pattern developed from the short radial lengths at upper tree heights had an agreement value of 2.25. Duncan's multiple range test indicated a significant difference (α=0.05) in agreement between the key-year patterns representing the two extremes.

Sample Size

Eight long radii from lower tree heights or 12 short radii from upper tree heights would be needed to achieve an adequate amount of agreement with the white ash key-year pattern. This conclusion is based on the following procedures.

Agreement was tested using successively smaller sample sizes between 16 and 8. Each sample size was represented by every possible combination of sixteen trees. Agreement was determined for each combination. The mean and standard deviation of the kappa statistic was determined for each sample size (Fig. 5). There was a decreasing amount of agreement with the white ash key-year pattern as the sample size was reduced. The agreement for the long radii at lower tree heights was consistently greater than the short radii at upper tree heights. The key-year pattern composed of 8 long radii at lower tree heights has slightly more agreement than does 16 short radii at upper tree heights. A sample size of at least 12 short radii at upper tree heights would

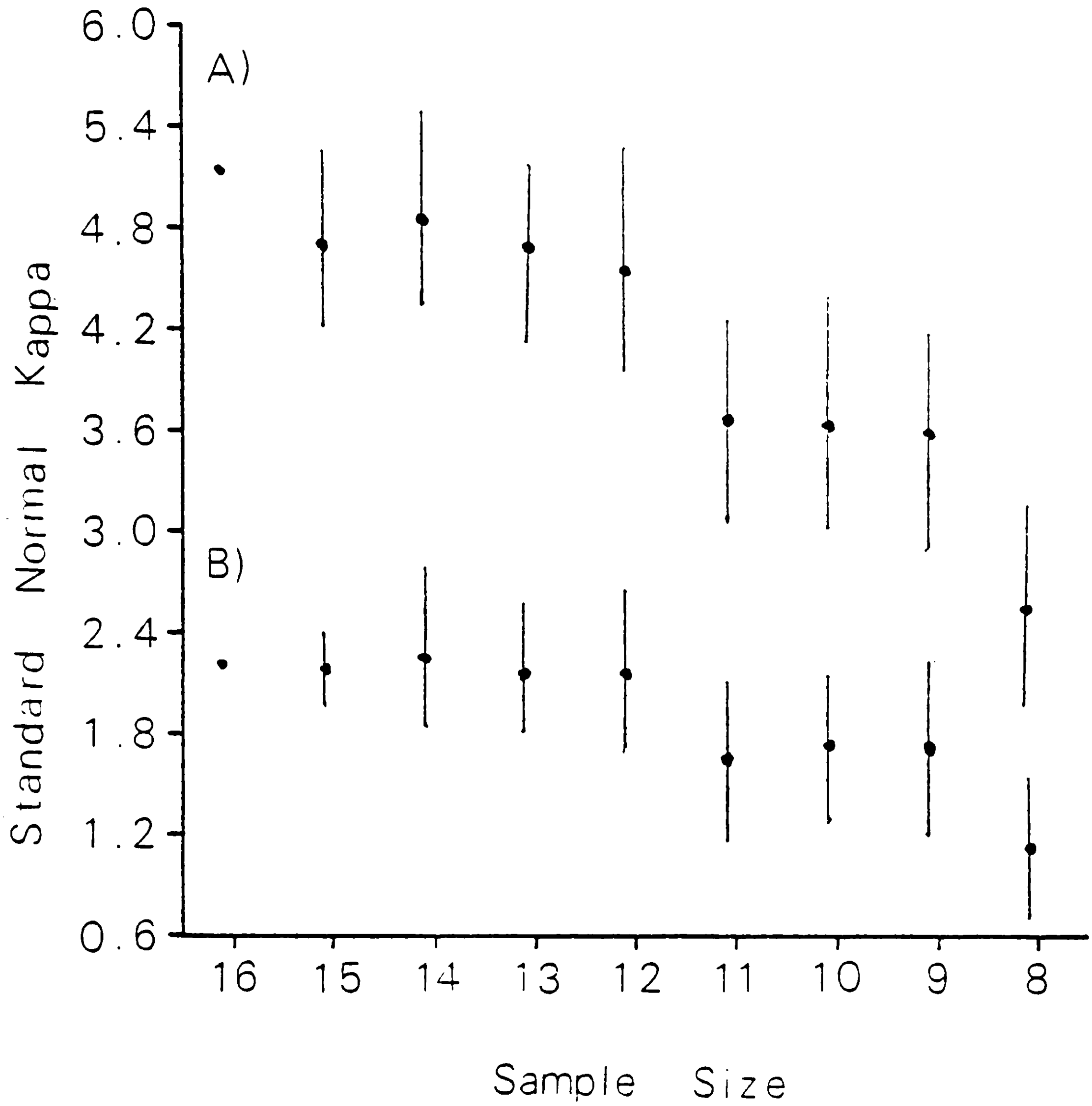

Figure 5. The upper curve a) shows agreements (kappa values), expressed as the mean and one standard deviation, between the white ash key-year pattern and the long radii from lower tree heights. The lower curve b) shows agreements between the white ash key-year pattern and the short radii at upper tree heights.

be needed to achieve the "minumum" agreement level because of the drop in agreement at 11 short radii at upper tree heights.

A sample size ranging from 12 to 15 radii from unknown heights and radial lengths should provide a reasonable estimate of the standard tree growth. Under more controlled circumstances (e.g. sampling entire disks), 8 samples taken from lower heights along long radial lengths should have an adequate amount of agreement to reflect tree growth. Since the sample size of 7 was not tested it can not definitely be said that 7 would not have the same amount of agreement as 8. However, the author feels that one sample from 8 trees should be the cut-off point for long radii from upper tree heights.

Discussion

Sample Preparation

Obtaining and processing wood samples is probably the most important step in the process of establishing a key-year pattern. Chain-sawing disks from recently felled or dead trees provides a good method of collecting samples. A disk allows the researcher to chose the radius; defects and abnormalities can be avoided. A recent logging operation provides an abundance of logs and tree stumps from which samples may be taken.

Increment-boring is a useful method of sampling but leaves the researcher no choice except removing multiple samples from individual trees in order that the sample finally chosen is defect-free. Increment-boring may be done on living trees, whereas removing an entire disk requires a recently-felled tree or an old tree stump. The researcher using the increment-borer has to use his own judgement as to the age of the tree to be sampled. This method may frequently miss many small old trees while wasting time on large young trees. Increment-boring is a rather random method of sampling and should only be used if an adequate number of recently-felled trees are not available.

Band-sawing a 2 by 2 cm (3/4 by 3/4 inch) radius from each disk taken in the field and sanding a fine surface has proven to be an excellent method of preparing and storing large quantities of samples. A fine furniture polish conceals small scratches on the surface of most types of wood making growth-ring measurements much easier. A strong variable intensity light also aids in the measuring process.

In general, a good defect-free sample with a clean smooth surface, good equipment and an experienced person is needed for the best mesurements of growth rings.

The White Ash Key-Year Pattern

The white ash key-year pattern was derived from 12 radii from each of 16 white ash trees. The white ash key-year pattern was used to test the "quality" of key-year patterns constructed from samples taken from a given height or along a given radius. Its implications to research are much greater than its use in this paper, however.

Future studies could make use of the white ash key-year pattern to predict growth rates of future stands of white ash in Montgomery County. These predictions in growth could be used to arrive at cost-benefit ratios for land owners thinking about planting white ash.

The white ash key-year pattern could be used in future dendroclimatogical studies after being correlated with present weather data. Fritts (1976) has done a great deal of work in this area in the arid southwest.

The white ash key-year pattern may be useful to entomologists desiring an accurate representation of tree growth for studies of the effects of phytophagus insects as well as their ecology and population dynamics. Tree species that are susceptible to a given insect attack can be compared with unsusceptible trees in order to show volume losses, biological implications or to compute frequencies of infestation (Reeks and Barter 1951). An entomologist desiring to observe the reaction of white ash to a known insect outbreak could compare the white ash key-year pattern with a key-year pattern constructed from ancther species that is known not to be effected by the insect.

The white ash key-year pattern may be useful in computing a risk rating for forest fires in Montgomery County, based on correlations with records of past fires. A fire index could be made to determine how severe a given fire season might be, based on the growth that occurred during the past growing season. Ferguson (1979) showed that key-year patterns from Montgomery and Surry Counties, Virginia and past fire records were in agreement (based on the number of fires and the acres burned).

The white ash key-year pattern may be useful in developing the probability of success or failure of agricultural crops within a specified period cf time, based on correlations of past crop records. In short, the white ash key-year pattern or the actual mean growth for the 16 trees may be an accurate representation of the environmental, climatic and the biotic influences on tree growth and could be used by entomologists, foresters, biologists, climatologists, historians, or anyone else who may need such data.

Sampling from Three Tree Heights

The researcher should not be overly cautious of sampling from different heights; there was no significant difference between the white ash key-year pattern and the key-year pattern composed of radii from the various heights. When it is convenient, sampling could be done at lower tree heights because of the slightly higher agreement found there. These findings agree with the studies of Fritts (1965) and Laar (1976) who found less agreement in radii taken from higher positions in the tree. Sampling at breast height (1.3 m (4.25 ft) above ground) should yield excellent results. When hollow or rotten centers are encountered the sample should be taken at upper tree heights.

Sampling Off-centered Piths

The long radii had significantly higher agreement with the white ash key-year pattern than did the other lengths. For this reason it is important to sample along the long radius when possible. When sampling whole disks the long radius can easily be band-sawed out. If the increment-boring sampling method is used, multiple samples should be taken to obtain the longest radius. Because of the longer radius on the uphill side of hardwood trees (caused by the reactions of compression and tension-wood), samples should be taken on the uphill side. On steep slopes or with leaning hardwood trees the sample should be taken on the uphill side. If sampling softwoods the sample should be taken on the downhill side (Panshin and Zeeuw, 1964)

Sample Size

The number of trees that should be sampled is dependent on the objective of the study and on the type and number of trees that are available. If a few (8-12) living trees are available, multiple increment-cores should be taken from each tree. When several living trees (> 12) are available, one sample should be taken from each tree. If sampling from stumps or from log ends, the longest radius from each of 8-10 disks would be necessary to construct a key-year pattern. When a very few samples (< 8) are available, the researcher may develop a key-year pattern by using several samples from each tree. Construction of a key-year pattern using less than 8 trees would be risky and should be used cautiously.

Conclusion and Recommendations

In conclusion, higher agreement was found between the white ash key-year pattern and radii from lower tree heights. However, no significant differnence was found in the amount of agreement of the key-year patterns from the lower, middle, and upper tree heights.

Increasing agreement was found with increasing radial lengths. The key-year patterns constructed using the long radial lengths were significantly higher in agreement than the medium long or the short radial-length groups. There was no significant difference between the medium long and the short radial-length group.

There was found to be more than twice the amount of agreement in the long radii at lower tree heights then in the short radii at upper tree heights key-year pattern. At least 8 trees were needed if the samples were taken from the long radii at lower tree heigths. Twelve trees would have to be used if the samples were from the short radii at upper tree heights. A sample taken from any height or radial length from each of 12-15 trees should yield a key-year pattern that simulates standard tree growth.

Future research in the development and use of the key-year pattern should concentrate on the following areas of study:

A. The influence of geography on the key-year pattern,
B. The influence of using various species of trees in the construction of key-year patterns,
C. The types of error encountered by researchers using the dendrochronometer,
D. Insect-tree growth-weather relations,
E. Disease-tree growth-weather relations,
F. Agricultural crops-soil moisture-tree growth relations,
G. The influence of stand thinnings or other disturbances on key-year patterns, and
H. The identification of missing or false growth rings.

The research presented in this paper should greatly improve the efficiency and the use of the key-year pattern.

Appendix

Appendix A. The white ash key-year pattern, based on the percentage of agreement of relative ring widths occurring in a given year exceeding the binomial criterion ($\alpha = 0.10$).[1]

Year	Sample Size #	Relative Ring Widths + #	0 #	- #	Agreement %	Binomial Criterion %	Key Years
1976	182	33	7	142	78.0	55.5	-
1975	182	137	1	44	75.3	55.5	+
1974	182	53	3	126	69.2	55.5	-
1973	182	133	2	47	73.1	55.5	+
1972	182	112	6	64	61.5	55.5	+
1971	182	166	3	13	91.2	55.5	+
1970	182	112	4	66	61.5	55.5	+
1969	182	20	5	157	86.3	55.5	-
1968	182	120	5	57	65.9	55.5	+
1967	182	153	4	25	84.1	55.5	+
1966	182	81	2	99	54.4	55.5	0
1965	182	63	5	114	62.6	55.5	-
1964	182	67	6	109	59.9	55.5	-
1963	182	82	5	95	52.2	55.5	0
1962	182	93	5	84	51.1	55.5	0
1961	182	73	4	105	57.7	55.5	-
1960	182	15	3	164	90.1	55.5	-
1959	182	33	2	147	80.8	55.5	-
1958	182	119	5	58	65.4	55.5	+
1957	182	91	1	90	50.0	55.5	0
1956	182	100	9	73	54.9	55.5	0
1955	182	111	5	66	61.0	55.5	+
1954	182	38	2	142	78.0	55.5	-
1953	182	147	4	31	80.8	55.5	+
1952	182	21	4	157	86.3	55.5	-
1951	182	128	2	52	70.3	55.5	+
1950	182	123	3	56	67.6	55.5	+

"0" key years are those years in which the percent agreement did not exceed the binomial criterion.

Appendix A. Continued.

Year	Sample Size #	Relative Ring Widths + #	0 #	- #	Agreement %	Bincmial Criterion %	Key Years
1949	182	33	1	148	81.3	55.5	-
1948	182	131	4	47	72.0	55.5	+
1947	182	65	2	115	63.2	55.5	-
1946	182	84	6	92	50.5	55.5	0
1945	182	115	1	66	63.2	55.5	+
1944	182	48	3	131	72.0	55.5	-
1943	182	91	0	91	50.0	55.5	0
1942	182	85	4	93	51.1	55.5	0
1941	170	80	7	83	48.8	55.3	0
1940	170	127	4	39	74.7	55.3	+
1939	170	30	4	136	80.0	55.3	-
1938	170	114	1	55	67.1	55.3	+
1937	170	117	3	50	68.8	55.3	+
1936	170	127	1	42	74.7	55.3	+
1935	170	46	0	124	72.9	55.3	-
1934	148	75	5	68	50.7	56.1	0
1933	148	58	5	85	57.4	56.1	-
1932	148	85	5	60	57.4	56.1	+
1931	136	110	3	25	80.9	55.9	+
1930	136	41	1	90	66.2	55.9	-
1929	136	45	5	86	63.2	55.9	-
1928	136	82	5	51	60.3	55.9	+
1927	136	89	3	41	65.4	55.9	+
1926	136	56	6	77	56.6	55.9	-
1925	136	25	3	109	80.1	55.9	-
1924	136	127	2	8	93.4	55.9	+
1923	136	37	1	98	72.1	55.9	-
1922	136	36	1	100	73.5	55.9	-
1921	136	41	0	89	65.4	55.9	-
1920	125	80	6	41	64.0	56.8	+

Appendix A. Continued.

Year	Sample Size	Relative Ring Widths				Binomial Criterion	Key Years
		+	0	-	Agreement		
	#	#	#	#	%	%	
1919	125	98	4	26	78.4	56.8	+
1918	125	12	1	109	87.2	56.8	-
1917	125	18	4	107	85.6	56.8	-
1916	125	62	0	59	49.6	56.8	0
1915	125	119	4	6	95.2	56.8	+
1914	125	5	0	120	96.0	56.8	-
1913	114	79	0	34	69.3	57.0	+
1912	103	60	1	43	58.3	57.3	+
1911	103	18	0	85	82.5	57.3	-
1910	103	82	0	20	79.6	57.3	+
1909	103	61	1	41	59.2	57.3	+
1908	103	33	1	68	66.0	57.3	-
1907	91	77	2	14	84.6	58.2	+
1906	91	34	0	57	62.6	58.2	-
1905	79	26	0	52	65.8	58.2	-
1904	79	28	1	50	63.3	58.2	-
1903	79	60	1	18	75.9	58.2	+

[1] For a given year, if the percent agreement is greater than the Binomial Criterion that year is classified as a (+/-) key year.

Appendix B. The key-year pattern of individual trees, based on four radii from the upper height.

Year	Tree Number															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1976	-	-	-	0	-	0	0	-	0	-	0	-	0	-	-	-
1975	+	+	+	0	+	+	0	0	0	0	+	0	0	0	0	0
1974	0	-	0	0	0	0	+	-	0	-	0	0	0	0	-	0
1973	0	0	0	0	0	+	0	0	+	0	0	0	+	0	0	0
1972	0	+	+	0	+	0	0	+	0	0	0	+	0	0	0	0
1971	+	+	0	+	+	0	0	0	0	0	+	+	+	0	+	0
1970	+	+	0	0	0	0	0	0	0	+	0	0	0	-	0	0
1969	0	-	-	-	-	0	-	-	0	-	-	0	0	0	-	-
1968	+	+	+	0	0	-	0	0	0	0	0	+	0	0	0	+
1967	+	+	+	0	+	0	+	0	+	+	+	+	+	0	0	+
1966	0	+	+	-	0	0	0	-	0	-	0	0	+	0	0	-
1965	0	-	-	+	-	0	0	-	0	+	-	0	0	0	0	0
1964	-	0	0	0	0	-	-	+	0	-	-	0	-	0	0	-
1963	0	0	0	0	0	0	0	0	0	0	0	-	0	-	+	0
1962	0	+	+	-	+	0	0	-	-	0	+	-	0	+	0	0
1961	0	-	-	0	-	+	-	0	0	+	-	+	0	-	0	0
1960	0	-	-	-	-	-	-	0	0	-	-	0	0	-	0	0
1959	0	0	-	+	-	-	0	-	0	-	-	0	0	0	0	-
1958	0	0	+	-	0	0	0	+	0	+	0	+	0	+	0	+
1957	-	0	+	+	0	-	0	0	0	0	+	-	0	-	0	0
1956	0	+	0	-	0	0	0	0	0	+	-	-	+	0	0	0
1955	0	+	0	0	0	0	+	0	+	0	0	0	-	0	0	0
1954	0	-	-	0	0	-	0	0	-	-	0	0	0	+	0	0
1953	0	0	0	0	+	+	+	0	+	+	+	+	0	0	0	-
1952	0	-	-	-	-	0	-	-	-	-	0	-	0	0	0	-
1951	0	-	0	+	-	0	+	0	0	0	+	+	+	0	0	0
1950	+	+	+	0	+	+	0	+	0	+	+	+	0	0	0	+

Appendix B. Continued.

Year	Tree Number															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1949	-	-	-	0	0	-	-	0	-	0	-	-	-	0	0	-
1948	0	+	+	+	0	0	+	0	0	0	0	0	+	0	+	0
1947	0	-	0	0	-	+	0	0	0	0	0	0	0	-	-	0
1946	0	+	0	0	0	0	0	0	+	-	-	0	0	0	0	-
1945	+	+	0	0	+	0	0	+	0	+	+	0	0	0	0	+
1944	0	-	-	0	0	0	0	-	-	0	0	-	0	0	0	0
1943	+	0	0	+	0	0	-	0	0	0	0	0	-	0	0	0
1942	0	0	0	+	0	-	+	0	0	0	+	+	0	0	0	0
1941	0	0	-	-	.	+	-	0	0	+	-	0	0	0	0	0
1940	+	+	0	+	.	+	-	+	+	0	+	+	0	+	0	+
1939	-	-	0	0	.	-	0	0	-	-	-	-	0	-	0	0
1938	+	-	0	0	.	+	0	0	0	+	+	+	+	0	0	0
1937	0	+	0	0	.	0	0	+	+	0	0	0	+	0	0	0
1936	-	-	0	0	.	+	+	0	0	0	+	0	0	+	+	0
1935	0	0	-	0	.	0	-	0	0	0	0	0	-	0	0	0
1934	0	.	-	-	.	0	+	+	+	-	.	0	+	+	0	+
1934	0	.	-	-	.	0	+	+	+	-	.	0	+	+	0	+
1932	-	.	0	+	.	+	0	+	+	0	.	0	0	0	-	-
1931	.	.	+	+	.	0	+	+	-	+	.	+	+	0	0	+
1930	.	.	-	0	.	-	-	0	-	-	.	0	0	-	0	+
1929	.	.	0	0	.	0	0	0	0	0	.	0	0	0	0	-
1928	.	.	+	0	.	-	+	0	+	-	.	+	-	0	0	-
1927	.	.	0	+	.	+	+	-	+	+	.	0	+	0	0	0
1926	.	.	0	0	.	0	-	0	-	0	.	0	+	0	0	+
1925	.	.	-	-	.	-	0	-	-	0	.	0	0	0	-	-
1924	.	.	+	+	.	+	+	+	+	0	.	+	+	+	+	+
1923	.	.	-	0	.	0	-	+	0	0	.	-	0	-	0	0
1922	.	.	-	0	.	-	0	0	-	0	.	-	0	-	0	0
1921	.	.	0	0	.	-	0	-	0	-	.	0	+	0	+	-
1920	.	.	0	+	.	+	0	0	0	.	.	0	0	0	0	0

A "." indicates the end of data for a given tree.

Appendix B. Continued.

Year	Tree Number															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1919	.	.	+	0	.	+	0	0	+	.	.	-	0	0	0	0
1918	.	.	-	-	.	-	0	0	-	.	.	0	-	-	0	0
1917	.	.	0	0	.	-	-	-	-	.	.	0	0	-	0	0
1916	.	.	0	+	.	0	+	0	-	.	.	0	-	0	0	0
1915	.	.	+	+	.	+	+	+	+	.	.	+	+	+	+	+
1913	.	.	+	+	.	+	.	0	+	.	.	0	0	+	-	-
1914	.	.	-	0	.	-	-	-	-	.	.	-	-	-	0	-
1912	.	.	0	0	.	0	.	+	0	.	.	0	+	0	0	.
1911	.	.	-	0	.	-	.	0	-	.	.	0	-	-	0	.
1910	.	.	0	+	.	+	.	+	+	.	.	0	0	+	0	.
1909	.	.	+	0	.	0	.	0	0	.	.	0	+	0	0	.
1908	.	.	0	0	.	-	.	0	-	.	.	0	-	0	0	.
1907	.	.	+	0	.	+	.	-	+	.	.	+	+	0	.	.
1906	.	.	+	0	.	-	.	0	0	.	.	0	-	-	.	.
1905	.	.	0	0	.	0	.	+	-	.	.	.	-	-	.	.
1904	.	.	+	-	.	-	.	-	+	.	.	.	0	0	.	.
1903	.	.	+	0	.	-	.	+	+	.	.	.	0	0	.	.

Appendix C. The key-year pattern of individual trees, based on four radii from the middle tree height.

Year	Tree Number															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1976	-	-	-	0	-	0	-	-	0	-	0	-	0	-	0	-
1975	+	+	+	+	0	+	0	0	0	+	+	0	0	+	+	0
1974	0	-	0	-	-	0	+	-	-	-	0	0	0	0	-	-
1973	0	-	0	0	0	+	+	+	+	+	+	+	0	0	0	+
1972	0	+	+	0	+	0	0	0	0	0	0	+	-	+	+	0
1971	+	+	+	+	+	+	+	+	+	+	0	+	+	+	+	+
1970	+	0	+	+	+	0	-	0	0	0	-	0	0	-	+	0
1969	0	-	-	-	-	0	0	0	0	0	-	-	0	0	-	-
1968	+	+	+	+	0	0	0	0	0	0	-	+	0	0	+	+
1967	+	+	0	-	+	0	0	+	0	0	+	+	0	0	+	+
1966	-	0	0	0	0	-	0	-	0	0	+	0	0	0	0	-
1965	0	-	-	+	0	0	-	-	0	0	-	0	0	0	-	0
1964	-	-	0	0	0	0	-	+	+	0	-	0	0	0	0	0
1963	0	0	0	0	+	0	0	0	0	-	+	0	+	-	0	0
1962	0	+	+	0	0	0	0	-	-	+	+	-	0	0	0	0
1961	+	-	-	0	-	0	0	0	0	+	-	+	+	0	-	0
1960	0	-	-	-	-	-	-	-	-	-	-	0	-	-	0	-
1959	-	-	0	-	-	-	0	-	0	-	-	-	0	0	0	0
1957	-	+	+	0	0	0	0	0	0	0	+	-	-	-	+	0
1956	+	+	0	+	+	0	+	0	0	+	-	0	0	+	0	0
1955	0	+	+	0	+	0	+	0	0	0	+	0	0	0	0	0
1954	0	-	-	0	-	-	-	-	0	-	0	-	0	0	0	0
1953	+	+	+	0	+	+	+	+	0	+	0	+	0	0	0	0
1952	-	-	-	-	-	-	0	-	0	-	-	-	0	+	-	-
1951	0	0	0	+	0	0	+	+	0	+	+	+	0	+	0	+
1950	0	+	0	0	+	0	-	+	0	0	+	0	0	0	+	+

Appendix C. Continued.

Year	Tree Number															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1949	0	-	0	0	0	-	-	0	0	0	-	-	0	-	-	-
1948	0	+	+	+	+	+	+	0	0	0	+	0	0	+	+	0
1947	-	-	0	+	-	+	0	-	0	-	0	0	0	-	+	0
1946	0	+	0	0	0	0	0	0	0	0	-	0	0	0	-	-
1945	+	+	0	-	+	-	-	+	0	+	+	0	+	0	+	+
1944	0	-	0	0	-	0	-	-	-	0	0	-	0	0	0	0
1943	+	-	+	+	0	-	0	0	0	0	-	0	0	-	0	0
1942	0	0	0	0	-	0	+	-	0	-	+	0	0	0	-	+
1941	0	+	0	0	.	+	-	+	0	0	-	0	-	0	0	0
1940	+	+	+	0	.	+	-	+	+	0	+	+	0	0	+	+
1939	-	-	0	+	.	-	-	-	-	-	-	-	-	0	-	0
1938	0	0	-	0	.	+	0	0	0	0	+	+	+	0	+	0
1937	+	0	0	+	.	0	0	0	0	0	0	0	0	0	+	+
1936	0	0	+	0	.	+	+	0	0	0	+	0	0	0	0	0
1935	-	-	0	0	.	-	-	+	0	0	0	0	0	-	-	0
1934	0	.	0	0	.	0	+	+	0	+	.	0	-	0	0	0
1933	0	.	0	-	.	0	-	0	0	0	.	-	0	0	0	0
1932	-	.	+	+	.	0	+	0	+	0	.	0	0	+	-	-
1931	.	.	0	0	.	-	-	+	-	0	.	-	-	-	-	0
1930	.	.	+	-	.	0	0	+	-	-	.	-	0	0	-	-
1929	.	.	+	-	.	0	0	+	-	-	.	-	0	0	-	-
1928	.	.	0	0	.	-	+	-	+	0	.	+	0	+	0	-
1927	.	.	0	+	.	+	0	0	0	+	.	0	0	0	+	0
1926	.	.	0	-	.	0	0	0	0	0	.	0	0	0	0	+
1925	.	.	-	-	.	-	0	0	-	0	.	-	0	0	-	-
1924	.	.	+	0	.	+	+	0	+	0	.	+	0	+	+	0
1923	.	.	-	0	.	0	-	0	0	0	.	-	0	-	0	0
1922	.	.	-	-	.	-	-	0	-	0	.	-	0	-	0	+
1921	.	.	0	-	.	-	0	-	0	-	.	0	+	0	0	-
1920	.	.	0	0	.	0	0	0	0	.	.	0	0	+	0	0

Appendix C. Continued.

Year	Tree Number															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1919	.	.	+	+	.	+	+	0	+	.	.	+	0	0	0	+
1918	.	.	-	-	.	-	0	-	-	.	.	-	-	0	-	0
1917	.	.	0	0	.	-	-	0	-	.	.	-	0	-	-	0
1916	.	.	0	0	.	+	+	0	0	.	.	0	0	0	0	-
1915	.	.	+	+	.	+	+	0	+	.	.	+	0	+	+	+
1914	.	.	-	-	.	-	-	0	-	.	.	-	-	-	-	-
1913	.	.	+	+	.	0	.	+	+	.	.	0	0	+	0	+
1912	.	.	-	0	.	+	.	0	0	.	.	-	+	0	0	.
1911	.	.	-	0	.	-	.	0	-	.	.	-	0	-	-	.
1910	.	.	0	+	.	+	.	+	+	.	.	+	0	0	0	.
1909	.	.	+	0	.	0	.	0	+	.	.	0	0	0	0	.
1908	.	.	0	-	.	-	.	0	-	.	.	-	0	-	0	.
1907	.	.	+	+	.	+	.	0	+	.	.	+	0	+	.	.
1906	.	.	+	0	.	0	.	0	0	.	.	0	-	-	.	.
1905	.	.	-	0	.	-	.	0	0	.	.	.	-	0	.	.
1904	.	.	+	-	.	-	.	0	0	.	.	.	-	-	.	.
1903	.	.	+	0	.	+	.	+	0	.	.	.	0	+	.	.

Appendix D. The key-year pattern of individual trees, based on 4 radii from the lower tree height.

Year	Tree Number															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1976	-	-	-	0	0	-	0	-	-	-	0	-	0	-	0	-
1975	+	+	+	+	+	0	0	0	0	+	+	0	+	+	0	0
1974	0	-	0	0	0	-	0	-	-	0	0	0	+	0	-	0
1973	0	-	0	0	+	+	+	+	0	+	+	+	-	+	+	+
1972	0	+	0	0	0	+	+	0	-	-	0	+	0	+	+	-
1971	0	+	+	+	+	0	+	+	+	+	+	+	+	+	+	+
1970	+	0	+	+	+	+	0	0	0	+	0	0	0	-	+	0
1969	0	-	-	-	-	-	-	-	0	-	-	-	-	0	-	-
1968	+	+	+	0	+	-	-	0	-	0	0	+	0	0	0	0
1967	+	+	+	0	+	0	+	+	+	+	+	+	+	+	0	+
1966	0	0	-	-	0	0	0	0	+	0	+	0	0	0	-	-
1965	0	-	-	0	0	0	-	-	-	+	-	0	0	-	0	+
1964	0	-	0	+	0	-	-	+	+	-	-	-	0	+	+	0
1963	-	0	0	-	+	0	0	+	0	-	0	0	+	-	0	-
1962	0	+	0	0	0	0	+	-	0	0	+	-	0	0	0	0
1961	0	-	0	0	-	+	-	0	0	+	-	0	0	-	0	0
1960	0	-	-	-	-	-	-	0	-	-	-	-	-	-	0	-
1959	0	-	-	-	-	-	-	-	-	0	-	0	0	0	-	-
1958	0	-	0	+	0	0	+	+	+	+	+	0	0	0	+	0
1957	0	0	+	+	0	0	0	-	0	0	+	-	0	0	0	0
1956	0	+	-	0	0	0	+	-	0	0	0	-	0	0	-	+
1955	0	0	+	+	0	0	+	-	0	+	+	0	-	-	0	0
1954	-	-	-	0	-	-	-	-	0	-	-	-	0	+	-	-
1953	+	+	+	0	+	+	+	+	0	+	+	+	0	-	+	+
1952	-	-	-	-	-	-	0	-	-	-	-	0	0	+	-	-
1951	+	0	0	+	-	0	+	0	0	+	+	+	0	+	+	+
1950	0	+	0	0	+	+	-	0	0	+	0	-	-	-	0	0

Appendix D. Continued.

Year	Tree Number															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1949	+	-	0	0	0	-	-	0	-	0	-	-	0	-	0	0
1948	0	+	+	0	0	+	+	+	0	0	+	0	+	0	-	0
1947	0	-	0	+	0	+	0	-	0	0	0	0	-	0	0	-
1946	0	+	0	+	0	0	+	-	+	0	-	+	+	0	-	-
1945	0	0	-	0	0	-	-	0	0	+	+	-	0	0	0	+
1944	0	0	-	-	+	0	0	0	0	0	0	-	-	-	0	0
1943	+	0	0	+	0	0	0	0	+	0	-	+	0	-	+	0
1942	-	-	-	0	-	0	+	0	0	0	+	-	0	0	0	0
1941	0	+	0	0	0	+	0	0	0	0	0	0	0	0	0	-
1940	+	+	+	+	0	0	-	0	+	0	+	0	-	0	0	+
1939	-	-	0	0	0	-	-	-	-	-	0	0	0	0	0	-
1938	+	0	-	+	0	+	0	0	+	0	+	0	0	+	+	0
1937	+	+	-	0	0	0	0	0	0	+	0	0	0	0	+	+
1936	0	+	+	+	0	+	+	+	0	+	+	+	0	+	+	0
1935	-	-	0	-	0	-	-	0	0	0	0	-	0	-	-	0
1934	0	0	0	0	0	0	+	0	0	-	0	0	0	-	0	0
1933	0	0	0	0	0	0	0	0	0	0	0	0	+	+	-	+
1932	-	0	0	+	0	+	+	0	+	-	0	0	0	+	-	-
1931	0	0	0	0	0	+	+	+	0	+	0	0	0	+	+	+
1930	0	0	0	+	0	-	-	+	-	0	0	0	0	-	-	+
1929	0	0	-	-	0	0	0	-	-	0	0	0	0	0	-	0
1928	0	0	+	+	0	-	+	0	+	0	0	+	0	+	+	0
1927	0	0	-	0	0	+	+	-	0	+	0	0	+	-	+	0
1926	0	0	-	-	0	0	0	-	0	+	0	0	0	-	0	+
1925	0	0	-	-	0	-	+	-	0	-	0	0	0	-	-	-
1924	0	0	+	+	0	+	+	+	+	+	0	+	0	+	+	+
1923	0	0	-	0	0	0	-	0	0	-	0	-	-	-	0	-
1922	0	0	0	-	0	-	-	+	-	+	0	-	0	-	0	+
1921	0	0	0	-	0	-	0	-	0	-	0	0	0	-	0	0
1920	0	0	+	0	0	+	0	0	+	0	0	-	0	+	0	0

Appendix D. Continued.

Year	Tree Number															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1919	0	0	0	+	0	+	+	+	+	0	0	0	0	0	+	+
1918	0	0	-	-	0	0	-	-	-	0	0	-	0	-	-	-
1917	0	0	-	-	0	-	-	-	-	0	0	-	0	-	0	0
1916	0	0	0	0	0	+	0	0	0	0	0	-	0	+	0	-
1915	0	0	+	+	0	+	+	+	+	0	0	+	0	+	0	0
1914	0	0	-	0	0	-	-	-	-	0	0	-	0	-	-	-
1913	0	0	0	+	0	+	0	+	0	0	0	0	0	+	0	0
1912	0	0	0	0	0	+	0	+	0	0	0	-	0	0	-	0
1911	0	0	0	0	0	-	0	0	-	0	0	-	0	-	0	0
1910	0	0	0	+	0	0	0	0	+	0	0	0	0	+	0	0
1909	0	0	0	0	0	+	0	-	+	0	0	0	0	0	0	0
1908	0	0	0	-	0	0	0	+	-	0	0	0	0	0	+	0
1907	0	0	+	+	0	+	0	0	+	0	0	+	0	0	0	0
1906	0	0	0	-	0	-	0	+	0	0	0	-	-	0	0	0
1905	0	0	0	0	0	0	0	0	+	0	0	0	-	-	0	0
1904	0	0	+	-	0	-	0	0	0	0	0	0	0	0	0	0
1903	0	0	0	-	0	+	0	0	+	0	0	0	+	0	0	0

Appendix E. The comparison of the white ash key-year pattern with the key-year patterns from the upper, middle, and lower heights from each tree.

Height	Key Year	White Ash Key-Year Pattern			
		+	0	-	Sum
Upper	+	187	33	21	241
	0	220	102	215	537
	-	23	32	172	227
	Sum	421	188	396	1005
Middle	+	202	34	22	258
	0	204	103	182	489
	-	24	30	204	258
	Sum	421	188	396	1005
Lower	+	334	32	21	279
	0	175	102	168	445
	-	41	33	207	281
	Sum	421	188	396	1005

Appendix F. The probability of occurrence of the observed agreements and disagreements between the white ash key-year pattern and the key-year patterns developed from the upper, middle, and lower tree height radii.

Height	Key Year	White Ash Key Year Pattern			
		+	0	-	Sum
Upper	+	0.1861	0.0328	0.0209	0.2398
	0	0.2189	0.1015	0.2139	0.5343
	-	0.0229	0.0318	0.1711	0.2259
	Sum	0.4279	0.1662	0.4060	1.0000
Middle	+	0.2010	0.0338	0.0219	0.2567
	0	0.2030	0.1025	0.1811	0.4866
	-	0.0239	0.0299	0.2030	0.2567
	Sum	0.4279	0.1662	0.4060	1.0000
Lower	+	0.2129	0.0318	0.0328	0.2776
	0	0.1741	0.1015	0.1672	0.4428
	-	0.0408	0.0328	0.2060	0.2796
	Sum	0.4279	0.1662	0.4060	1.0000

Appendix G. The key-year pattern of individual trees, based on 3 radii from the long radius-length group.

Year	Tree Number 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1976	-	-	-	0	-	-	0	-	0	-	-	-	0	-	0	-
1975	+	+	+	+	+	0	-	-	0	+	+	0	+	+	0	+
1974	0	-	0	0	0	0	+	0	0	-	0	0	0	-	-	-
1973	0	0	0	0	0	+	0	+	0	+	0	+	0	+	+	+
1972	0	+	+	0	0	+	0	+	0	0	+	+	-	+	0	-
1971	+	+	0	+	+	0	+	+	+	0	+	+	+	+	+	0
1970	+	0	+	+	+	0	0	0	0	+	0	0	0	-	+	0
1969	0	-	-	-	-	0	-	-	0	-	-	-	-	-	-	-
1968	+	+	+	0	+	-	0	0	0	0	0	+	0	+	0	0
1967	+	+	+	0	+	0	0	+	0	+	+	+	+	+	0	+
1966	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-	-
1965	0	-	-	+	0	0	-	-	-	0	-	0	0	0	0	0
1964	-	-	0	0	0	-	-	+	+	-	-	-	0	0	+	0
1963	-	-	0	0	0	0	0	+	0	-	0	-	+	0	0	-
1962	-	+	0	0	0	-	0	-	0	0	+	-	0	0	0	0
1961	+	-	0	-	-	0	-	0	-	+	-	+	+	-	0	0
1960	-	-	-	-	-	-	-	-	-	-	-	0	-	0	0	0
1959	0	-	-	0	-	-	0	-	-	0	-	0	0	0	0	0
1958	0	0	+	0	0	-	0	0	0	+	+	+	0	+	+	0
1957	0	+	+	+	0	0	0	0	0	0	+	-	0	-	+	0
1956	0	+	-	0	0	0	+	-	0	+	0	-	+	0	-	+
1955	0	+	0	+	+	0	+	-	+	0	+	0	0	0	0	0
1954	0	-	-	-	-	-	0	-	-	-	-	0	-	0	-	0
1953	+	+	0	+	+	+	+	+	0	+	+	+	0	0	+	+
1952	-	-	-	-	-	-	0	-	-	-	-	-	-	0	-	-
1951	0	0	0	+	-	0	+	+	0	+	+	+	+	+	0	0
1950	0	+	+	+	+	+	-	+	0	+	+	0	-	0	0	0

Appendix G. Continued.

Year	Tree Number															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1949	0	-	-	0	-	-	-	-	-	0	-	-	-	-	-	-
1948	0	+	+	0	+	0	+	+	0	0	+	0	+	+	0	0
1947	0	-	-	0	-	+	-	-	0	-	-	0	0	-	0	0
1946	+	+	0	+	0	0	+	0	0	0	-	+	0	-	-	-
1945	0	0	0	0	+	-	0	0	0	+	+	-	+	+	0	+
1944	0	-	0	-	0	0	-	0	-	+	0	-	-	-	0	-
1943	+	0	0	+	0	0	0	-	+	0	0	0	-	-	0	0
1942	0	0	-	0	-	-	+	0	0	0	+	0	0	0	-	0
1941	0	0	0	0	.	+	0	0	0	0	0	0	-	0	+	0
1940	+	+	+	0	.	0	-	0	+	0	+	+	0	+	0	+
1939	-	-	0	0	.	-	-	-	-	0	-	-	-	0	-	-
1938	+	0	-	0	.	+	0	+	0	0	+	+	+	+	+	+
1937	+	0	0	0	.	0	+	0	0	+	+	+	0	0	+	+
1936	0	0	+	0	.	+	+	0	+	0	+	+	+	0	+	0
1935	-	-	-	0	.	-	-	+	-	0	0	-	-	0	-	0
1934	0	.	0	0	.	-	+	+	0	0	.	0	0	0	-	0
1933	0	.	-	-	.	0	0	-	0	0	.	-	0	+	-	0
1932	-	.	+	+	.	+	+	+	+	0	.	0	0	+	-	-
1931	.	.	+	+	.	0	+	+	0	0	.	+	+	0	+	+
1930	.	.	0	0	.	-	-	+	-	-	.	0	-	-	-	0
1929	.	.	0	-	.	0	0	0	0	-	.	-	0	-	0	-
1928	.	.	0	0	.	-	+	-	+	0	.	+	-	+	+	-
1927	.	.	0	+	.	+	+	-	0	+	.	0	+	0	+	0
1926	.	.	0	0	.	-	0	0	-	0	.	0	+	-	0	+
1925	.	.	-	-	.	-	0	-	-	0	.	0	0	-	-	-
1924	.	.	+	+	.	+	+	+	+	0	.	+	+	+	+	+
1923	.	.	-	0	.	0	-	+	0	0	.	-	0	-	0	0
1922	.	.	-	-	.	-	0	0	-	0	.	-	-	-	0	0
1921	.	.	0	0	.	-	+	-	-	-	.	-	+	0	0	-
1920	.	.	0	0	.	+	-	0	0	.	.	0	+	0	+	+

Appendix G. Continued.

Year	Tree Number															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1919	.	.	+	+	.	+	+	+	+	.	.	0	+	+	+	0
1918	.	.	−	−	.	0	−	−	−	.	.	−	−	−	−	−
1917	.	.	−	−	.	−	−	−	−	.	.	−	−	−	−	0
1916	.	.	0	+	.	+	+	+	0	.	.	0	0	+	0	0
1915	.	.	+	+	.	+	+	+	+	.	.	+	0	+	+	0
1914	.	.	−	−	.	−	−	−	−	.	.	−	−	−	−	−
1913	.	.	+	+	.	+	.	+	+	.	.	0	+	+	0	0
1912	.	.	−	−	.	0	.	+	0	.	.	0	+	0	0	.
1911	.	.	−	0	.	−	.	−	−	.	.	−	0	−	−	.
1910	.	.	0	+	.	+	.	+	+	.	.	+	0	+	0	.
1909	.	.	+	0	.	+	.	0	+	.	.	0	0	0	−	.
1908	.	.	0	−	.	−	.	0	−	.	.	0	0	−	+	.
1907	.	.	+	+	.	+	.	−	+	.	.	+	+	+	.	.
1906	.	.	+	−	.	−	.	0	+	.	.	−	−	−	.	.
1905	.	.	0	+	.	0	.	+	0	.	.	.	−	−	.	.
1904	.	.	0	−	.	−	.	0	0	.	.	.	−	0	.	.
1903	.	.	+	−	.	+	.	+	+	.	.	.	+	+	.	.

Appendix H. The key-year pattern of individual trees, based on three radii from the medium-long radial length group.

Year	Tree Number															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1976	-	-	-	0	-	-	0	-	0	-	-	-	0	-	0	-
1975	+	+	+	+	+	0	-	-	0	+	+	0	+	+	0	+
1974	0	-	0	0	0	0	+	0	0	-	0	0	0	-	-	-
1973	0	0	0	0	0	+	0	+	0	+	0	+	0	+	+	+
1972	0	+	+	0	0	+	0	+	0	0	+	+	-	+	0	-
1971	+	+	0	+	+	0	+	+	+	0	+	+	+	+	+	0
1970	+	0	+	+	+	0	0	0	0	+	0	0	0	-	+	0
1969	0	-	-	-	-	0	-	-	0	-	-	-	-	-	-	-
1968	+	+	+	0	+	-	0	0	0	0	0	+	0	+	0	0
1967	+	+	+	0	+	0	0	+	0	+	+	+	+	+	0	+
1966	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-	-
1965	0	-	-	+	0	0	-	-	-	0	-	0	0	0	0	0
1964	-	-	0	0	0	-	-	+	+	-	-	-	0	0	+	0
1963	-	-	0	0	0	0	0	+	0	-	0	-	+	0	0	-
1962	-	+	0	0	0	-	0	-	0	0	+	-	0	0	0	0
1961	+	-	0	-	-	0	-	0	-	+	-	+	+	-	0	0
1960	-	-	-	-	-	-	-	-	-	-	-	0	-	0	0	0
1959	0	-	-	0	-	-	0	-	-	0	-	0	0	0	0	0
1958	0	0	+	0	0	-	0	0	0	+	+	+	0	+	+	0
1957	0	+	+	+	0	0	0	0	0	0	+	-	0	-	+	0
1956	0	+	-	0	0	0	+	-	0	+	0	-	+	0	-	+
1955	0	+	0	+	+	0	+	-	+	0	+	0	0	0	0	0
1954	0	-	-	-	-	-	0	-	-	-	-	0	-	0	-	0
1953	+	+	0	+	+	+	+	+	0	+	+	+	0	0	+	+
1952	-	-	-	-	-	-	0	-	-	-	-	-	-	0	-	-
1951	0	0	0	+	-	0	+	+	0	+	+	+	+	+	0	0
1950	0	+	+	+	+	+	-	+	0	+	+	0	-	0	0	0

Appendix H. Continued.

Year	Tree Number															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1949	0	-	-	0	-	-	-	-	-	0	-	-	-	-	-	-
1948	0	+	+	0	+	0	+	+	0	0	+	0	+	+	0	0
1947	0	-	-	0	-	+	-	-	0	-	-	0	0	-	0	0
1946	+	+	0	+	0	0	+	0	0	0	-	+	0	-	-	-
1945	0	0	0	0	+	-	0	0	0	+	+	-	+	+	0	+
1944	0	-	0	-	0	0	-	0	-	+	0	-	-	-	0	-
1943	+	0	0	+	0	0	0	-	+	0	0	0	-	-	0	0
1942	0	0	-	0	-	-	+	0	0	0	+	0	0	0	-	0
1941	0	0	0	0	.	+	0	0	0	0	0	0	-	0	+	0
1940	+	+	+	0	.	0	-	0	+	0	+	+	0	+	0	+
1939	-	-	0	0	.	-	-	-	-	0	-	-	-	0	-	-
1938	+	0	-	0	.	+	0	+	0	0	+	+	+	+	+	+
1937	+	0	0	0	.	0	+	0	0	+	+	+	0	0	+	+
1936	0	0	+	0	.	+	+	0	+	0	+	+	+	0	+	0
1935	-	-	-	0	.	-	-	+	-	0	0	-	-	0	-	0
1934	0	.	0	0	.	-	+	+	0	0	.	0	0	0	-	0
1933	0	.	-	-	.	0	0	-	0	0	.	-	0	+	-	0
1932	-	.	+	+	.	+	+	+	+	0	.	0	0	+	-	-
1931	.	.	+	+	.	0	+	+	0	0	.	+	+	0	+	+
1930	.	.	0	0	.	-	-	+	-	-	.	0	-	-	-	0
1929	.	.	0	-	.	0	0	0	0	-	.	-	0	-	0	-
1928	.	.	0	0	.	-	+	-	+	0	.	+	-	+	+	-
1927	.	.	0	+	.	+	+	-	0	+	.	0	+	0	+	0
1926	.	.	0	0	.	-	0	0	-	0	.	0	+	-	0	+
1925	.	.	-	-	.	-	0	-	-	0	.	0	0	-	-	-
1924	.	.	+	+	.	+	+	+	+	0	.	+	+	+	+	+
1923	.	.	-	0	.	0	-	+	0	0	.	-	0	-	0	0
1922	.	.	-	-	.	-	0	0	-	0	.	-	-	-	0	0
1921	.	.	0	0	.	-	+	-	-	-	.	-	+	0	0	-
1920	.	.	0	0	.	+	-	0	0	.	.	0	+	0	+	+

Appendix H. Continued.

Year	Tree Number															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1919	.	.	+	+	.	+	+	+	+	.	.	0	+	+	+	0
1918	.	.	−	−	.	0	−	−	−	.	.	−	−	−	−	−
1917	.	.	−	−	.	−	−	−	−	.	.	−	−	−	−	0
1916	.	.	0	+	.	+	+	+	0	.	.	0	0	+	0	0
1915	.	.	+	+	.	+	+	+	+	.	.	+	0	+	+	0
1914	.	.	−	−	.	−	−	−	−	.	.	−	−	−	−	−
1913	.	.	+	+	.	+	.	+	+	.	.	0	+	+	0	0
1912	.	.	−	−	.	0	.	+	0	.	.	0	+	0	0	.
1911	.	.	−	0	.	−	.	−	−	.	.	−	0	−	−	.
1910	.	.	0	+	.	+	.	+	+	.	.	+	0	+	0	.
1909	.	.	+	0	.	+	.	0	+	.	.	0	0	0	−	.
1908	.	.	0	−	.	−	.	0	−	.	.	0	0	−	+	.
1907	.	.	+	+	.	+	.	−	+	.	.	+	+	+	.	.
1906	.	.	+	−	.	−	.	0	+	.	.	−	−	−	.	.
1905	.	.	0	+	.	0	.	+	0	.	.	.	−	−	.	.
1904	.	.	0	−	.	−	.	0	0	.	.	.	−	0	.	.
1903	.	.	+	−	.	+	.	+	+	.	.	.	+	+	.	.

Appendix I. The key-year pattern of individual trees, based on 3 radii from the short radial length group.

Year	Tree Number															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1976	-	-	0	0	-	0	0	-	0	-	0	-	0	-	-	0
1975	+	+	+	0	+	+	0	0	+	+	+	0	0	+	0	0
1974	-	-	0	0	-	0	0	-	-	-	0	0	+	0	-	0
1973	0	0	0	+	0	+	+	+	+	+	+	+	0	0	0	0
1972	0	+	0	-	0	0	0	0	0	-	-	+	0	0	+	0
1971	0	+	+	+	+	+	+	0	+	+	+	0	+	+	+	0
1970	+	0	+	0	+	+	-	0	-	0	0	0	0	-	0	0
1969	0	-	-	-	-	-	0	-	0	0	-	-	0	0	-	-
1968	+	+	+	0	0	0	-	0	0	0	-	+	+	-	0	+
1967	+	+	+	0	+	0	+	+	+	0	+	0	0	0	+	+
1966	0	0	0	0	0	-	0	0	0	0	+	0	0	+	0	-
1965	0	-	-	0	0	+	-	-	0	+	-	0	+	0	-	0
1964	0	-	0	0	0	-	-	+	0	0	-	-	-	0	+	0
1963	0	0	0	0	+	0	0	0	0	0	+	0	0	-	0	-
1962	0	+	+	-	0	-	0	-	-	0	+	-	0	0	0	+
1961	0	-	-	+	-	+	-	0	0	+	-	0	0	-	-	0
1960	0	-	-	-	-	-	-	-	0	-	-	0	-	-	0	-
1959	0	0	-	0	-	-	0	-	-	-	-	-	+	0	-	-
1958	0	0	0	0	+	0	0	+	+	+	0	+	0	+	+	+
1957	-	0	+	+	0	0	0	-	0	0	+	-	-	-	0	0
1956	0	+	-	0	0	+	0	0	-	0	+	0	0	0	0	0
1955	0	0	+	0	+	+	+	0	0	+	0	0	-	0	0	0
1954	0	-	-	0	0	-	-	0	-	-	0	-	+	+	-	0
1953	+	+	+	0	+	+	+	0	+	+	0	+	0	0	0	0
1952	0	-	-	-	-	-	+	-	0	-	-	0	0	+	-	-
1951	0	0	-	+	0	-	+	+	0	+	+	+	0	+	+	+
1950	0	+	0	0	+	+	-	0	-	0	0	0	0	-	0	+

Appendix I. Continued.

Year	Tree Number															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1949	0	-	0	0	0	-	-	+	0	0	-	-	0	-	-	-
1948	+	+	+	0	0	+	+	0	0	-	0	0	0	0	0	0
1947	0	-	-	0	-	+	0	0	-	0	0	0	0	0	0	0
1946	-	+	0	0	0	0	0	-	0	0	-	0	0	+	0	-
1945	+	+	-	0	+	0	-	+	0	+	+	0	+	0	0	+
1944	-	0	-	0	0	0	-	-	-	-	0	-	-	0	0	0
1943	+	0	+	+	0	-	0	0	0	0	-	+	0	-	0	-
1942	0	0	0	+	-	0	+	0	0	0	+	0	0	+	0	+
1941	0	+	-	0	.	+	0	0	0	0	-	-	0	0	0	-
1940	+	+	+	0	.	+	-	+	0	0	+	+	0	0	0	+
1939	-	-	+	0	.	-	-	0	-	-	0	0	0	0	0	-
1938	+	0	0	0	.	+	0	0	0	0	+	0	0	0	0	0
1937	0	+	0	0	.	0	0	0	+	+	-	-	0	0	0	0
1936	-	0	+	0	.	+	+	+	0	0	+	0	0	+	0	0
1935	-	0	0	0	.	-	-	0	0	0	0	0	-	0	0	-
1934	0	.	0	0	.	+	+	+	0	0	.	0	0	0	0	+
1933	+	.	-	0	.	-	-	-	0	0	.	0	0	0	0	+
1932	-	.	0	+	.	+	0	0	+	0	.	+	0	+	-	-
1931	.	.	0	+	.	+	+	+	-	+	.	+	0	0	0	+
1930	.	.	0	0	.	-	-	+	-	0	.	0	0	-	-	0
1929	.	.	0	-	.	-	+	0	-	0	.	0	0	0	-	0
1928	.	.	+	+	.	0	+	0	+	-	.	+	0	0	0	-
1927	.	.	-	+	.	+	0	0	0	+	.	0	0	0	+	0
1926	.	.	-	0	.	0	-	-	0	+	.	0	+	0	0	+
1925	.	.	-	-	.	-	0	0	0	0	.	0	0	0	-	-
1924	.	.	+	+	.	+	+	0	+	0	.	+	0	+	+	0
1923	.	.	-	0	.	+	-	0	0	-	.	-	-	-	0	-
1922	.	.	-	0	.	-	-	0	-	+	.	-	+	-	0	+
1921	.	.	0	0	.	-	0	0	0	-	.	0	0	0	0	-
1920	.	.	0	0	.	0	0	0	0	.	.	-	+	0	0	0

Appendix I. Continued.

Year	Tree Number															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1919	.	.	+	0	.	+	+	0	+	.	.	0	-	0	0	+
1918	.	.	-	0	.	-	0	0	-	.	.	0	-	-	-	0
1917	.	.	-	-	.	-	-	0	-	.	.	-	+	-	0	-
1916	.	.	0	0	.	+	+	0	-	.	.	0	-	0	0	-
1915	.	.	+	+	.	+	+	0	+	.	.	+	+	+	+	+
1914	.	.	-	0	.	-	-	0	-	.	.	-	-	-	-	-
1913	.	.	0	0	.	+	.	+	+	.	.	0	0	+	-	-
1912	.	.	-	0	.	+	.	0	0	.	.	0	+	0	0	.
1911	.	.	-	0	.	-	.	0	-	.	.	0	-	-	0	.
1910	.	.	-	+	.	0	.	0	+	.	.	0	0	0	0	.
1909	.	.	+	0	.	0	.	0	+	.	.	0	0	0	0	.
1908	.	.	0	0	.	0	.	0	-	.	.	0	0	0	0	.
1907	.	.	+	0	.	+	.	0	+	.	.	+	0	+	.	.
1906	.	.	0	0	.	-	.	0	0	.	.	0	-	0	.	.
1905	.	.	0	-	.	0	.	0	0	.	.	.	-	0	.	.
1904	.	.	+	-	.	-	.	0	0	.	.	.	0	-	.	.
1903	.	.	0	-	.	+	.	0	+	.	.	.	0	0	.	.

Appendix J. The comparison of the white ash key-year pattern with the key-year patterns from the long, medium-long, and short radial length groups.

Radius Length Group	Key Year	White Ash Key-Year Pattern			
		+	0	-	Sum
Long	+	235	33	24	292
	0	166	103	145	414
	-	29	31	239	299
	Sum	421	188	396	1005
Medium Long	+	207	31	40	278
	0	187	104	166	457
	-	36	32	202	270
	Sum	421	188	396	1005
Short	+	182	33	30	245
	0	212	102	189	503
	-	36	32	189	257
	Sum	421	188	396	1005

Appendix K. The probability of occurrence of the observed agreements and disagreements (from Appendix J) between the white ash key-year pattern and the key-year patterns from the long, medium-long, and short radial length groups.

Radius Length Group	Key Year	White Ash Key-Year Pattern			
		+	0	-	Sum
Long	+	0.2338	0.0328	0.0239	0.2905
	0	0.1652	0.1025	0.1443	0.4119
	-	0.0289	0.0308	0.2378	0.2975
	Sum	0.4279	0.1662	0.4060	1.0000
Medium Long	+	0.2060	0.0308	0.0398	0.2766
	0	0.1861	0.1035	0.1652	0.4547
	-	0.0358	0.0318	0.2010	0.2687
	Sum	0.4279	0.1662	0.4060	1.0000
Short	+	0.1811	0.0328	0.0299	0.2766
	0	0.2109	0.1015	0.1881	0.5005
	-	0.0358	0.0318	0.1881	0.2557
	Sum	0.4279	0.1662	0.4060	1.0000

Appendix L. The key-year pattern from 16 white ash trees taken at lower tree heights along the long radius.

Year	Sample Size #	Relative Ring Widths + #	0 #	- #	Agreement %	Binomial Criterion %	Key Years
1976	16	3	0	13	81.3	75.0	-
1975	16	11	0	5	68.8	75.0	0
1974	16	6	1	9	56.3	75.0	0
1973	16	9	1	6	56.3	75.0	0
1972	16	11	0	5	68.8	75.0	0
1971	16	15	0	1	93.8	75.0	+
1970	16	13	0	3	81.3	75.0	+
1969	16	1	0	15	93.8	75.0	-
1968	16	8	1	7	50.0	75.0	0
1967	16	13	0	3	81.3	75.0	+
1966	16	6	0	10	62.5	75.0	0
1965	16	6	0	10	62.5	75.0	0
1964	16	6	0	10	62.5	75.0	0
1963	16	6	0	10	62.5	75.0	0
1962	16	8	1	7	50.0	75.0	0
1961	16	9	0	7	56.3	75.0	0
1960	16	0	1	15	93.8	75.0	-
1959	16	2	1	13	81.3	75.0	-
1958	16	13	0	3	81.3	75.0	+
1957	16	8	0	8	50.0	75.0	0
1956	16	10	0	6	62.5	75.0	0
1955	16	11	0	5	68.8	75.0	0
1954	16	0	1	15	93.8	75.0	-
1953	16	14	0	2	87.5	75.0	+
1952	16	1	1	14	87.5	75.0	-
1951	16	13	1	2	81.3	75.0	+
1950	16	10	0	6	62.5	75.0	0

Appendix L. Continued.

Year	Sample Size #	Relative Ring Widths + #	0 #	- #	Agreement %	Binomial Criterion %	Key Years
1949	16	2	0	14	87.5	75.0	-
1948	16	12	0	4	75.0	75.0	+
1947	16	4	0	12	75.0	75.0	-
1946	16	9	1	6	56.3	75.0	0
1945	16	8	0	8	50.0	75.0	0
1944	16	5	0	11	68.8	75.0	0
1943	16	10	0	6	62.5	75.0	0
1942	16	4	0	12	75.0	75.0	-
1941	15	10	1	4	66.7	73.3	0
1940	15	9	0	6	60.0	73.3	0
1939	15	1	2	12	80.0	73.3	-
1938	15	13	0	2	86.7	73.3	+
1937	15	10	0	5	66.7	73.3	0
1936	15	15	0	0	100.0	73.3	+
1935	15	2	0	13	86.7	73.3	-
1934	13	3	0	10	76.9	76.9	-
1933	13	5	0	8	61.5	76.9	0
1932	13	8	0	5	61.5	76.9	0
1931	12	12	0	0	100.0	75.0	+
1930	12	4	0	8	66.7	75.0	0
1929	12	3	0	9	75.0	75.0	-
1928	12	8	0	4	66.7	75.0	0
1927	12	8	0	4	66.7	75.0	0
1926	12	4	1	7	58.3	75.0	0
1925	12	3	0	9	75.0	75.0	-
1924	12	12	0	0	100.0	75.0	+
1923	12	5	0	7	58.3	75.0	0
1922	12	3	0	9	75.0	75.0	-
1921	12	3	0	9	75.0	75.0	-
1920	11	8	1	2	72.7	81.8	0

Appendix L. Continued.

Year	Sample Size #	Relative Ring Widths + #	0 #	- #	Agreement %	Binomial Criterion %	Key Years
1919	11	11	0	0	100.0	81.8	+
1918	11	1	0	10	90.9	81.8	-
1917	11	1	0	10	90.9	81.8	-
1916	11	8	0	3	72.7	81.8	0
1915	11	9	0	2	81.8	81.8	+
1914	11	0	0	11	100.0	81.8	-
1913	10	9	0	1	90.0	80.0	+
1912	9	4	0	5	75.1	77.8	0
1911	9	1	0	8	88.9	77.8	-
1910	9	9	0	0	100.0	77.8	+
1909	9	5	0	4	75.1	77.8	0
1908	9	4	0	5	75.1	77.8	0
1907	8	7	0	1	87.5	87.5	+
1906	8	3	0	5	62.5	87.5	0
1905	7	4	0	3	57.1	85.7	0
1904	7	2	0	5	76.9	85.7	0
1903	7	6	0	1	85.7	85.7	+

Appendix M. The key-year pattern from 16 white ash trees taken at upper tree heights along the short radius.

Year	Sample Size #	Relative Ring Widths + #	0 #	- #	Agreement %	Binomial Criterion %	Key Years
1976	16	3	1	12	75.0	75.0	-
1975	16	10	0	6	62.5	75.0	0
1974	16	5	1	10	62.5	75.0	0
1973	16	13	0	3	81.3	75.0	+
1972	16	10	1	5	62.5	75.0	0
1971	16	14	0	2	87.5	75.0	+
1970	16	6	1	9	56.3	75.0	0
1969	16	1	1	14	87.5	75.0	-
1968	16	8	0	8	50.0	75.0	0
1967	16	14	0	2	87.5	75.0	+
1966	16	8	0	8	50.0	75.0	0
1965	16	8	1	7	50.0	75.0	0
1964	16	3	0	13	81.3	75.0	-
1963	16	10	0	6	62.5	75.0	0
1962	16	9	0	7	56.3	75.0	0
1961	16	8	0	8	50.0	75.0	0
1960	16	2	0	14	87.5	75.0	-
1959	16	6	0	10	62.5	75.0	0
1958	16	13	0	3	81.3	75.0	+
1957	16	5	0	11	68.8	75.0	0
1956	16	9	1	6	56.3	75.0	0
1955	16	10	0	6	62.5	75.0	0
1954	16	8	0	8	50.0	75.0	0
1953	16	11	1	4	68.8	75.0	0
1952	16	4	0	12	75.0	75.0	-
1951	16	11	0	5	68.8	75.0	0
1950	16	11	1	4	68.8	75.0	0

Appendix M. Continued.

Year	Sample Size #	Relative Ring Widths + #	0 #	- #	Agreement %	Binomial Criterion %	Key Years
1949	16	3	0	13	81.3	75.0	-
1948	16	10	0	6	62.5	75.0	0
1947	16	6	1	9	56.3	75.0	0
1946	16	5	0	11	68.8	75.0	0
1945	16	13	1	2	81.3	75.0	+
1944	16	3	0	13	81.3	75.0	-
1943	16	7	0	9	56.3	75.0	0
1942	16	10	1	5	62.5	75.0	0
1941	15	4	0	11	73.3	73.3	-
1940	15	12	0	3	80.0	73.3	+
1939	15	2	1	12	80.0	73.3	-
1938	15	11	0	4	73.3	73.3	+
1937	15	8	0	7	53.3	73.3	0
1936	15	9	0	6	60.0	73.3	0
1935	15	7	0	8	53.3	73.3	0
1934	13	8	0	5	61.5	76.9	0
1933	13	5	1	7	53.9	76.9	0
1932	13	7	0	6	53.9	76.9	0
1931	12	9	0	3	75.0	75.0	+
1930	12	5	0	7	58.3	75.0	0
1929	12	4	0	8	66.7	75.0	0
1928	12	6	0	6	50.0	75.0	0
1927	12	7	1	4	58.3	75.0	0
1926	12	6	0	6	50.0	75.0	0
1925	12	4	0	8	66.7	75.0	0
1924	12	11	0	1	91.7	75.0	+
1923	12	3	1	8	66.7	75.0	0
1922	12	4	0	8	66.7	75.0	0
1921	12	4	1	7	58.3	75.0	0
1920	11	5	0	6	54.55	81.8	0

Appendix M. Continued.

Year	Sample Size #	Relative Ring Widths + #	0 #	- #	Agreement %	Bincmial Criterion %	Key Years
1919	11	7	0	4	63.6	81.8	0
1918	11	2	1	8	72.7	81.8	0
1917	11	1	0	10	90.9	81.8	-
1916	11	5	1	5	45.5	81.8	0
1915	11	11	0	0	100.0	81.8	+
1914	11	1	0	10	90.9	81.8	-
1913	10	6	1	3	60.0	80.0	0
1912	9	6	0	3	66.7	77.8	0
1911	9	2	0	7	77.8	77.8	-
1910	9	6	0	3	66.7	77.8	0
1909	9	4	0	5	55.6	77.8	0
1908	9	5	0	4	55.6	77.8	0
1907	8	6	0	2	77.8	87.5	0
1906	8	2	0	6	77.8	87.5	0
1905	7	2	0	5	71.4	85.7	0
1904	7	3	0	4	57.1	85.7	0
1903	7	5	0	2	71.4	85.7	0

Appendix N. A comparison between the white ash key-year pattern and the key-year pattern composed of 16 samples taken from the long radii at lower tree heights and the short radii at upper tree heights.

Extremity Group	Key Year	White Ash Key-Year Pattern			
		+	0	-	Sum
Long Radii Lower Height	+	17	0	0	17
	0	15	9	13	37
	-	0	2	18	20
	Sum	32	11	31	74
Short Radii Upper Height	+	10	0	0	10
	0	22	10	20	52
	-	0	1	11	12
	Sum	32	11	31	74

Appendix O. The probability of occurrence of the observed agreements and disageements between the white ash key-year pattern and the key-year patterns composed of 16 samples taken from the long radii at lower tree heights and the short radii at the lower tree heights.

Extremity Group	Key Year	White Ash Key-Year Pattern			
		+	0	-	Sum
Long Radii Lower Height	+	0.2297	0.0000	0.0000	0.2297
	0	0.2027	0.1216	0.1757	0.5000
	-	0.0000	0.0270	0.2432	0.2702
	Sum	0.4324	0.1486	0.4189	1.0000
Short Radii Upper Height	+	0.1351	0.0000	0.0000	0.1351
	0	0.2973	0.1351	0.2703	0.7027
	-	0.0000	0.0135	0.1487	0.1622
	Sum	0.4324	0.1486	0.4190	1.0000

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Vita

John Gordon Fairservice Jr. was born in Livingston, Montana on December 14, 1952 to Mr and Mrs John G. Fairservice. His father joined the U.S. Army and received orders for Orleans, France. In 1957 the family moved to France and lived in Tavers, a small village outside Orleans. They lived there for 5 years and returned in 1963 to Newport News, Virginia. The author attended Denbigh High School and received his diploma in June 1971. He attended Thomas Nelson Community College between Fall 1971 and Spring 1974, receiving an Associate in Science in June. In September 1974 he began classes at Virginia Polytechnic Institute and State University toward a Bachelor of Science in Forestry and Wildlife. He specialized in Wildlife Management. He finished the requirements for his degree and received his degree in June 1977. He was accepted at VPI & SU as a graduate student in Entomology and began course work and research in September 1977.

John Gordon Fairservice, Jr.

The Devlopment of Sampling Methods

for Key-Year Patterns of

White Ash (<u>Fraxinus</u> <u>americana</u> L.)

by

John Gordon Fairservice, Jr.

(Abstract)

A key year is a year in which a significant number of trees had a wider or narrower growth ring than the previous year. A non-key year is a year which there was not a significant number of trees that had greater or less growth than the previous year. A key-year pattern is a series of key years that are separated in time by non-key years. Key-year patterns have proven useful in determining the date of construction of buildings of historical significance (Heikkenen 1980).

A white ash key-year pattern was constructed, using 4 radii from 3 tree heights of 16 trees. Radii from a tree height of 0.3 m (1 ft) above ground were found to have higher agreement with the white ash key-year pattern than radii from positions higher in the tree. Long radii (from off-centered piths) were found to have higher agreement than the shorter radii. The long radii from lower heights had

twice the level of agreement as the short radii at upper heights. The amount of agreement decreased as the number of trees used to construct the key-year pattern was dropped from 16 to 8. At least 8 samples of long radii from lower tree heights were needed to construct a key-year pattern. At least 12 samples were needed from short radii at upper tree heights to construct a key-year pattern. Twelve samples were sufficient to produce a key-year pattern, when sampling from unknown heights and radial lengths (i.e. log houses).