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A SIMPLE CROSSDATING PROGRAM FOR TREE-RING RESEARCH

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ABSTRACT

A crossdating program for tree-ring research has been written to compare ring patterns of individual trees and composites. The program written in FORTRAN calculates the *t* value for correlation at every point of overlap of the two chronologies. The program is small enough to be used on a routine basis with a large number of trees. As the chronologies must be free from errors, the program is more suited to the study of oaks than coniferous trees.

INTRODUCTION

Recent developments in dendrochronology in Europe, especially the construction of long standard chronologies from oak timbers, have created a demand for a straightforward, powerful correlation method.

The computer program described in this paper was devised to compare the ring patterns of individual timber samples with those of established chronologies whether floating or standard. It is also a powerful tool for establishing the position of highest correlation between the ring patterns of individual trees.

The program (Figure 1) is designed to be used for comparing the ring patterns of chronologies without missing or double rings. This is normally the case in oak chronologies from Europe (Huber and Giertz 1970; Baillie 1973). Where an error is suspected this must be checked before the program is used.

A standard program exists for the calculation of the percentage agreement coefficients at all positions of overlap between two chronologies (Eckstein and Bauch 1969). The drawback of the percentage agreement method is that it is non-parametric; while calculating a figure of merit for the similarity of the two ring patterns, it takes no account of the magnitudes of the year-to-year changes in ring width. Significant crossdating is only demonstrated by the percentage agreement method when there is a long overlap between two chronologies and the agreement figure is better than 60 percent. When comparisons of ring patterns of around 100 years length are made, the normal distribution of agreement coefficients resulting from random mis-matches tends to obscure the coefficient of true crossdating. Since with European oak the ring patterns are frequently of 100 to 200 years in length, a program was written to calculate the product moment correlation coefficient *r* at each position of overlap. This coefficient is parametric and thus takes account of the magnitudes of the yearly width variations. The value of *r* takes no account of the length of overlap, so the value of Student's *t* is calculated from *r* to introduce a measure of significance in relation to length of overlap.

The form presented here is the simplest version for the comparison of one chronology against a single longer chronology. It is written in FORTRAN IV and uses a card reader and line printer. Versions have been written for use on a teletype computer terminal and to handle more than one data set per run.

```
      MASTER CROS
C
C     STATISTICAL CROSS-DATING PROGRAM FOR TREE RING DATA WRITTEN BY
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C                      QUEEN'S UNIVERSITY BELFAST
C
      INTEGER NAMA(8),NAMB(8)
      DIMENSION A(500),B(250),C(750)
C
C     DIMENSIONS OF A AND B DETERMINE MAXIMUM LENGTHS OF SERIES THAT
C     CAN BE HANDLED
C
      COMMON A,B,C,AMEAN,BMEAN
C
C                             INPUT AND STANDARDIZATION
C                             ========================
C
C     READ SITE NAME
C
      READ(5,1)(NAMA(I),I=1,6)
    1 FORMAT(6A4)
C
C     READ NAME OR NUMBER OF FIRST TREE
C
      READ(5,101)NAMA(7),NAMA(8)
  101 FORMAT(2A4)
C
C     READ NUMBER OF YEARS IN FIRST TREE, AND DATE OF FIRST RING IF
C     KNOWN, IF DATE IS NOT KNOWN LEAVE BLANK
C
      READ(5,102)K,MDATE
  102 FORMAT(I3,I4)
      IF(MDATE)0,0,4
      IDATE=15
      GO TO 27
    4 IDATE = MDATE + 14
C
C     READ WIDTHS OF FIRST TREE
C
   27 READ(5,3)(A(I),I=1,K)
    3 FORMAT(25F3.0)
C
C     STANDARDIZATION OF FIRST TREE
C
      K=K-4
```

Figure 1. Listing of program CROS.

```
      AMEAN=0.0
      DO 7 I=1,K
      A(I)=ALOG(500*A(I+2)/(A(I)+A(I+1)+A(I+2)+A(I+3)+A(I+4)))
    7 AMEAN=AMEAN+A(I)
      AMEAN=AMEAN/K
C
C     READ DATA FOR SECOND TREE: SITE, NAME, YEARS, WIDTHS.
C
      READ(1,1)(NAMB(I),I=1,6)
      READ(1,101)NAMB(7),NAMB(8)
      READ(1,2)L
    2 FORMAT(I3)
      READ(1,3)(B(I),I=1,L)
C
C     STANDARDIZATION OF SECOND TREE
C
      L=L-4
      BMEAN=0.0
      DO 8 I=1,L
      B(I)=ALOG(500*B(I+2)/(B(I)+B(I+1)+B(I+2)+B(I+3)+B(I+4)))
    8 BMEAN=BMEAN+B(I)
      BMEAN=BMEAN/L
C
C                             COMPARISON SECTION
C                             ==================
C
C     SLIDE TREES PAST EACH OTHER AND CALL SURROUTINE CALR AT EACH POINT
C     OF OVERLAP.THIS IS DONE IN THREE STAGES.
C
      L9=L-9
      L11=L-11
      DO 12 NF=1,L11
   12 CALL CALR(NF,1,NF+10,L9-NF,NF+10,NF)
      L1=L-1
      KL=K-L+1
      DO 13 NG=1,KL
   13 CALL CALR(NG,NG,NG+L1,1,L,L11+NG)
      K10=K-10
      DO 14 NH=1,L-11
   14 CALL CALR(NH,KL+NH,K,1,L-NH,K10+NH)
C
C                             OUTPUT SECTION
C                             ==============
C
      WRITE(2,19)
```

Figure 1, *continued*

```
   19  FORMAT(1H1,//40X,34H CROSS DATING BY PROGRAM **CROSS**)
       WRITE(2,15)NAMA,NAMB
   15  FORMAT (1H0,20X,20H COMPARISON OF TREE ,8A4,5H AND ,8A4)
       IF(IDATE-15)0,0,20
       WRITE(2,21)
   21  FORMAT(/ 17H YEARS OF OVERLAP, 20X,27H 'T' VALUES FOR COMPARISONS)
       GO TO 23
   20  WRITE(2,22)
   22  FORMAT(/19H DATE OF OUTER YEAR,20X,27H 'T' VALUES FOR COMPARISONS)
   23  IEND = ((K+L-22)/10)*10
       DO 18 KD = 1,IEND,10
       K10=KD+9
       WRITE(2,16)IDATE,(C(I),I=KD,K10)
   16  FORMAT(2X,I4,6X,10F10.2)
   18  IDATE = IDATE + 10
C
C      VALUES OF 'T' ARE SCANNED FOR ANY OVER A PRESET VALUE OF 3.5
C      THESE VALUES ARE OUTPUT WITH THE OVERLAPS AS A SUMMARY
C
       DO 24 L=1,IEND
       IF(C(L)-3.5)24,24,0
       IF(MDATE)0,0,26
       LAP=L+14
       WRITE(2,25) C(L),LAP
   25  FORMAT(10X,6H 'T' =,F4.2,4H AT ,I4,17H YEARS OF OVERLAP)
       GO TO 24
   26  LAP=L+13+MDATE
       WRITE(2,28)C(L),LAP
   28  FORMAT(10X,6H 'T' =,F4.2,23H ,DATE OF OUTER YEAR = ,I4)
   24  CONTINUE
       WRITE(2,29)
   29  FORMAT(1H1)
       PAUSE
       END


       SUBROUTINE CALR (N,NQ,NS,NT,NV,NW)
C
C      CALR CALCULATES THE CORRELATION COEFICIENT AND 'T' VALUE
C      FOR EACH POSITION OF OVERLAP AS SET IN THE SUBROUTINE CALLS
C
       DIMENSION A(500),B(250),C(750)
       COMMON A,B,C,AMEAN,BMEAN
       S1=0.0
       S2=0.0
       S3=0.0
       JJ=NT-1
       DO 1II=NQ,NS
       XX=A(II)-AMEAN
       JJ=JJ+1
       YY=B(JJ)-BMEAN
       S1=S1+XX*XX
       S2=S2+YY*YY
       S3=S3+XX*YY
    1  CONTINUE
C
C      NEGATIVE CORRELATIONS ARE SET = 0.0
C
       IF(S3.LE.0.0)GO TO 2
       SIGX =SQRT(S1/NV)
       SIGY= SQRT(S2/NV)
       CAL 1=S3/(NV*SIGX*SIGY)
       CAL 2=SQRT(NV-2.0)
       CAL 3=SQRT(1-CAL1*CAL1)
       C(NW)=CAL1*CAL2/CAL3
       GO TO 3
    2  C(NW)=0.0
    3  RETURN
       END
       FINISH
```

Figure 1, *continued*

STANDARDIZATION AND CALCULATION OF *t*

The matching of two tree-ring patterns involves the cross-correlation of two sets of numerical ring widths. When mis-matched, the correlation between these sets approximates that between two sets of random numbers. When the ring patterns represent the same span of years the correlation should be high, assuming the trees have been growing under similar conditions.

If any set of values (x,y) shows a trend when plotted as co-ordinates, then x and y are said to be correlated. If the values of x increase and decrease when the values of y increase and decrease, then the correlation is positive. This is the expected condition for the ring widths of two trees growing over the same period of years. Thus the basic assumptions of the dendrochronological method argue for the use of a direct parametric correlation method. The degree of correlation between x and y is measured by r, the product moment correlation coefficient, defined thus

$$r = \frac{\Sigma_i x_i y_i - N\bar{x}\bar{y}}{\sqrt{(\Sigma_i x_i^2 - N\bar{x}^2)(\Sigma_i y_i^2 - N\bar{y}^2)}}$$

where $\bar{x}$ and $\bar{y}$ are the means of all the x and y values respectively. The calculation of Student's t provides a measure of the probability of the observed value of r having arisen by chance. The value of t is defined as

$$t = \frac{r\sqrt{N-2}}{\sqrt{1-r^2}}$$

where N is the number of degrees of freedom, in this case the number of years overlap between the ring patterns.

For the values of t obtained by this calculation to provide a valid measure of probability, the sets of values x and y must be bivariate-normal (Parker 1973). In order to satisfy this condition, any trends have to be removed from the basic data. The program carries out a simple standardization where each ring width is converted to a percentage of the mean of the five ring widths of which it is the centre value. In this form the data varies about a mean of 100 but is not normally distributed. Normalization is achieved by taking log to base e of the percentage figures. Sample sets of data treated in this way were tested for skewness and excess and were found to satisfy the conditions of normality. Probability levels can be obtained from tables of Student's t.

APPLICATIONS AND LIMITATIONS

As presented here program CROS uses relatively little computer store and running times are fast. It is designed for routine use in the crossdating of large numbers of timbers of unknown age. It is used by us for crossdating individuals and for crossdating against standard and floating chronologies. Its advantage over the percentage agreement calculation is that the distinction between true crossdating and random similarity is greatly enhanced and a much greater statistical confidence can be placed on the results. Table 1 shows a series of comparisons carried out by the two methods with the confidence limits indicated by each method. It can be seen that the confidence limits are in general several orders of magnitude higher in the case of the correlation coefficients. Even when the computer indicates a high degree of confidence in the crossdating, this must still be checked visually.

CROSS DATING BY PROGRAM **CROSS**

COMPARISON OF TREE HILLSBROUGH Q 538 AND HILLSBROUGH Q 536

YEARS OF OVERLAP	'T' VALUES FOR COMPARISONS									
15	0.00	0.00	0.00	0.59	0.27	0.41	0.00	0.10	0.66	0.00
25	0.00	0.75	0.12	0.00	0.94	0.00	0.94	0.68	0.00	0.00
35	2.22	0.90	0.00	0.00	0.00	1.66	0.45	0.00	0.61	0.62
45	0.00	0.00	2.11	0.00	0.00	1.13	1.47	0.65	0.00	0.00
55	1.32	2.03	0.00	0.00	2.59	0.14	0.00	1.27	0.55	0.00
65	0.00	1.61	0.00	0.00	0.75	0.00	0.53	0.00	0.00	0.00
75	0.25	0.40	0.00	1.47	0.00	0.00	2.28	0.99	0.00	0.00
85	0.57	0.53	0.89	0.00	0.00	0.00	1.16	1.89	0.00	0.00
95	0.28	1.46	0.00	0.00	1.22	0.36	0.00	1.19	0.00	0.00
105	1.76	0.80	0.00	0.00	1.31	0.31	0.17	1.57	0.00	0.00
115	1.63	0.61	0.00	1.52	0.00	0.00	0.64	2.93	0.00	0.00
125	0.95	0.00	0.24	1.09	0.00	0.00	0.41	0.03	0.00	1.52
135	1.76	0.00	0.00	0.00	0.05	1.62	0.06	0.00	0.00	0.00
145	0.36	2.16	0.00	0.00	0.00	1.52	1.12	0.00	0.00	0.75
155	1.32	1.06	0.00	0.00	0.00	0.00	1.50	1.36	0.00	0.07
165	0.00	0.00	0.00	0.44	0.21	0.36	0.77	0.00	0.00	2.07
175	1.47	0.00	0.00	0.00	0.00	5.29	1.95	0.00	0.00	0.61
185	1.26	0.72	0.52	0.00	0.00	1.63	0.91	0.00	0.00	0.00
195	1.14	0.26	0.00	0.57	0.00	0.42	0.00	0.00	0.00	1.77
205	0.75	0.00	0.00	1.66	1.05	0.00	0.00	0.00	0.17	2.60
215	0.47	0.00	0.00	1.31	0.94	0.00	0.51	0.00	0.00	1.89
225	0.11	0.32	0.84	0.00	0.00	0.48	0.00	0.19	0.28	0.50
235	0.00	0.00	2.55	0.38	2.83	0.00	0.00	0.00	2.61	0.00
245	0.88	0.00	1.21	0.78	1.52	0.11	0.00	0.00	0.45	0.40
255	0.37	0.00	0.00	0.13	0.03	0.19	0.00	0.57	0.00	0.00

'T' =5.29 AT 180 YEARS OF OVERLAP

CROSS DATING BY PROGRAM **CROSS**

COMPARISON OF TREE HILLSBROUGH Q 538 AND HILLSBROUGH Q 536

DATE OF OUTER YEAR	'T' VALUES FOR COMPARISONS									
1467	0.00	0.00	0.00	0.59	0.27	0.41	0.00	0.10	0.66	0.00
1477	0.00	0.75	0.12	0.00	0.94	0.00	0.94	0.68	0.00	0.00
1487	2.22	0.90	0.00	0.00	0.00	1.66	0.45	0.00	0.61	0.62
1497	0.00	0.00	2.11	0.00	0.00	1.13	1.47	0.65	0.00	0.00
1507	1.32	2.03	0.00	0.00	2.59	0.14	0.00	1.27	0.55	0.00
1517	0.00	1.61	0.00	0.00	0.75	0.00	0.53	0.00	0.00	0.00
1527	0.25	0.40	0.00	1.47	0.00	0.00	2.28	0.99	0.00	0.00
1537	0.57	0.53	0.89	0.00	0.00	0.00	1.16	1.89	0.00	0.00
1547	0.28	1.46	0.00	0.00	1.22	0.36	0.00	1.19	0.00	0.00
1557	1.76	0.80	0.00	0.00	1.31	0.31	0.17	1.57	0.00	0.00
1567	1.63	0.61	0.00	1.52	0.00	0.00	0.64	2.93	0.00	0.00
1577	0.95	0.00	0.24	1.09	0.00	0.00	0.41	0.03	0.00	1.52
1587	1.76	0.00	0.00	0.00	0.05	1.62	0.06	0.00	0.00	0.00
1597	0.36	2.16	0.00	0.00	0.00	1.52	1.12	0.00	0.00	0.75
1607	1.32	1.06	0.00	0.00	0.00	0.00	1.50	1.36	0.00	0.07
1617	0.00	0.00	0.00	0.44	0.21	0.36	0.77	0.00	0.00	2.07
1627	1.47	0.00	0.00	0.00	0.00	5.29	1.95	0.00	0.00	0.61
1637	1.26	0.72	0.52	0.00	0.00	1.63	0.91	0.00	0.00	0.00
1647	1.14	0.26	0.00	0.57	0.00	0.42	0.00	0.00	0.00	1.77
1657	0.75	0.00	0.00	1.66	1.05	0.00	0.00	0.00	0.17	2.60
1667	0.47	0.00	0.00	1.31	0.94	0.00	0.51	0.00	0.00	1.89
1677	0.11	0.32	0.84	0.00	0.00	0.48	0.00	0.19	0.28	0.50
1687	0.00	0.00	2.55	0.38	2.83	0.00	0.00	0.00	2.61	0.00
1697	0.88	0.00	1.21	0.78	1.52	0.11	0.00	0.00	0.45	0.40
1707	0.37	0.00	0.00	0.13	0.03	0.19	0.00	0.57	0.00	0.00

'T' =5.29 ,DATE OF OUTER YEAR = 1632

Figure 2. Output from program CROS showing result when chronologies are floating (above) and when the date of the longer one is known (below).

Table 1. Comparison of the results of testing crossdating by the percentage agreement method and by the calculation of *t* values.

Laboratory Numbers for Tree A	Tree B	Years of Overlap	Percent Agreement	Limits[1]	Students *t*	Limits[1]
537	538	160	65	10^{-4}	3.87	10^{-4}
535	542	156	65	10^{-3}	5.46	5×10^{-8}
536	538	106	65	10^{-3}	5.29	10^{-7}
547	535	116	63	10^{-2}	5.19	5×10^{-7}
536	537	114	62	10^{-2}	3.59	5×10^{-4}
542	537	157	58	10^{-2}	3.09	3×10^{-5}
553	542	119	56	10^{-1}	3.89	10^{-4}
536	544	122	55	10^{-1}	3.39	10^{-3}

[1] Figures in these columns indicate the probability of the percentage agreement or *t* value occurring randomly

INPUT AND OUTPUT

As both the nature of the computer peripherals and the data format at different institutions vary, the program is presented in the form used in the Palaeoecology Laboratory. The data is prepared on cards, one set per chronology. The first card of the set gives the title or site name of the set (6 A 4 Format)and the second card an identity number of sample name (2 A 4 Format). The third card gives the number of years in the series (up to 999) followed by the calendar year of the first measurement if known (I3, I4 Format). If the year columns are left blank the comparison is assumed to be between undated individuals and the results are given in terms of the number of years overlap. The remaining cards of the set contain the ring width measurements (25 F3.0 Format or 25 I 3 Format). The format cards can easily be changed to suit different data formats.

The two styles of output are shown in Figure 2. The upper one being a comparison of undated specimens, the lower one the same data with the year of the first ring measurement given. In the first output 'years of overlap' indicates the total number of years that the shorter chronology has been moved relative to the longer one. At the end of the table of *t* values there is a summary of all values greater than an arbitrary preset value of 3.5.

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REFERENCES

Baillie, Michael G. L.
1973 A dendrochronological study in Ireland with reference to the dating of Medieval and post-Medieval timbers. MS. Doctoral dissertation, Queen's University, Belfast.
Eckstein, D. and J. Bauch
1969 Bietrag zur Rationalisie-rung eines Dendrochronologischen Verfahrens und zur Analyse Seiner Aussagesicherheit. *Fortwiss* 88:230-50.
Huber, B. and V. Giertz
1970 Central European dendrochronology for the Middle Ages. In *Scientific Methods in Medieval Archaeology*, edited by Rainer Berger, pp. 201-12. University of California Press, Berkeley.
Parker, R. E.
1973 *Introductory statistics for biologists.* The Institute of Biology, Studies in Biology No. 43, London.