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Analysis of Tree Rings and Climatic Changes

Contemporary interest in climatic change exists for various reasons, among them knowing how adverse climatic conditions would affect the world's food production. In order to forecast future trends, past climatic patterns must be understood. Unfortunately, records necessary for this type of investigation are often relatively short. This paper examines the problem of extending existing records of rainfall into the past.

One source of these records is tree-ring widths.[1] At best, the width of a tree ring in any particular year is a function of several climatic variables as well as the biological ones. To be of value some means has to be developed to separate the climatic effects from the general variation in ring widths.

Many types of tree live to an age of several hundred years. If tree-ring widths are sensitive to rain and temperature, they provide a possible means of extending climatological records back in time. In semi-arid regions in particular it may be straightforward to obtain a simulated past rainfall series in this way because either rainfall or temperature is likely to be a limiting factor in tree growth. Since large areas of Southern Africa receive adequate rainfall to sustain satisfactory tree growth every year, our problem, therefore, is to simulate past rainfall in a non-arid zone, an exercise which is rendered difficult by the complexities of tree growth and its relationship with weather.

Method

Cross-sections of pine trees were sanded smooth in the field using a belt sander and portable generator. Twenty-four radii at 15°-intervals were marked off on a smoothed section of each sample. Only those radii that were approximately orthogonal to the rings they cut were used in the analysis as those radii that intersected rings at shallower angles were difficult to measure and to interpret. The section was then photographed with a 35 mm camera and high-contrast film (Fig.1). Ring widths were measured from the negatives in the laboratory using a travelling microscope. We prefer this method to that of direct measurement of the tree, since it has the advantage of providing easy storage of stable and reliable data. This is not the case when working from the wood, which changes its dimensions owing to shrinkage, splitting and swelling, Another advantage of this approach is that one is inclined to study large numbers of cross-sections, only bringing back to base enough logs to enable an examination of particular details.

The data were arranged as 14 columns of radial ring-widths plus a column of 20 annual rainfall totals. As there were as many ring widths as years of rainfall (but see later), we defined a data matrix of 20 rows (years) by 15 columns (14 radial measurements plus rainfall). The rainfall records were for the forest at Tzaneen, northern Transvaal, where the trees were sampled. They had been kept by the resident forester and are believed to be reliable. Planting and felling dates were also available, which removed any uncertainties over the age of the trees. This is important because it is not always the case, as is commonly assumed, that the number of rings corresponds exactly to the age of the tree.

In order to investigate any interrelationships within the data matrix, we chose the method of principal components analysis, which strictly is a mathematical data transformation technique and not a statistical one. By this means a new set of data is formed having as many rows and columns as did the original set. The first derived, principal component (PC) is that linear combination of the original variables that extracts as much variance as possible from the original data set. The second PC is the linear combination that extracts as much of the remaining variance as possible, and is also uncorrelated with the first component. This procedure is repeated until as many principal components have been derived as there were variables originally.

The advantage of this method is that if relationships exist within the original data matrix, a high percentage of the variance contained in that data set can be represented by only a few, derived components. If the original variables are standardised so that all have zero mean and unit variance, coefficients of the derived PCs can be scaled so as to represent the correlations between the two sets of variables.[2] Standardisation is carried out when scaling problems exist in the data, as in the present case where we included two different types of variable. It is common practice to refer to the coefficients as loadings; therefore, those original variables having high loadings on any particular component will be well represented by that component.

Whereas the matrix of loadings emphasises the original relationships between variables and components, the component scores place emphasis on the observations. These scores may be defined as

$$\xi_i = \sum_{j=1}^{p} l_{ij} x_j \qquad (1)$$

where $i = 1, 2, \ldots n$ and $k, j = 1, 2, \ldots p$. The x terms are the original variables (the 14 radii and rainfall), the l terms are the component coefficients, and n is the number of rings per radius. As the original variables are a time series, the scores are also a time series and therefore indicate the variation in wood growth, as measured by ring widths, and rainfall attributable to each year of the record. Only a few series need be examined because the first few components embody most of the available information.

For a given component it is possible that only some radii are highly loaded on it. Alternatively, rainfall may have a high loading whereas no radii have. Ideally, we require rainfall and all or some radii to be loaded on a common PC, in which case the component is a composite variable representing some relationship between the two. This situation is based on the assumption that of the various factors affecting growth, one can be associated with rainfall and the relationship isolated. In these circumstances we can then indirectly extend the rainfall record back in time by correlating it with the radii that are heavily loaded on the same PC as rainfall. If rainfall is loaded on a PC with no accompanying high loadings for radii, the method has obviously failed. Only in the case where all, or most, radii and rainfall are highly loaded on a single PC are we justified in taking a mean series of ring widths across radii as an indicator of rainfall. This is likely to be the case with tree samples from a semi-arid region.

The variances and related terms for the principal components are given in Table 1. There are as many PCs as there are

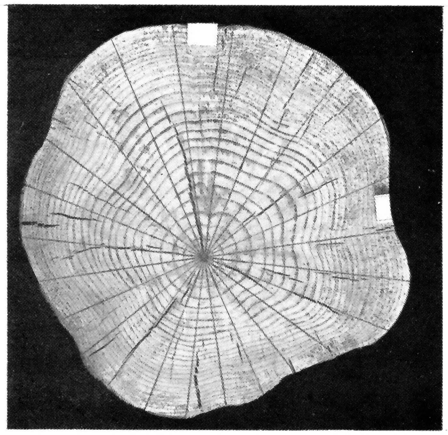

Fig. 1. The cross-section of the tree discussed in this paper, showing the radii marked off at 15-degree intervals. The two bough wounds are situated at the right-hand side of the

original standardised data matrix. The first three PCs account for 86% of the total variance, so we should lose little information if we represent the original variables by just these. It is common policy to consider only those PCs whose variances have values greater than unity, the others being taken to represent random variation or noise. Thus this procedure reduces the number of variables to be considered from 15 to 3.

A loading in excess of 0.5 is taken to be of particular value.[3] But for radius 16, all radii are equally well correlated with PC1 (Fig. 2*a*). By virtue of its negligible loading, rainfall is not related to this PC, which describes the general growth pattern of the tree (Fig. 3*a*). The second principal component, PC2, has radii 16 and 23 significantly correlated with it, together with rainfall (Fig. 2*b*). This PC also represents a weak compensatory action between radii 10, 11, and radii 16, 23 and rainfall. By this is meant that the region in which radii 10 and 11 are situated puts down less wood than average when radii 16 and 23 and rainfall are above average; the converse of this is also true. PC3 represents little more than rainfall variation (Fig. 2*c*) The only radii having anything but very low correlations with this principal component are 6, 16 and 20, but none of these is statistically significant.

It can be seen that PC2 amalgamates rainfall and growth. In a

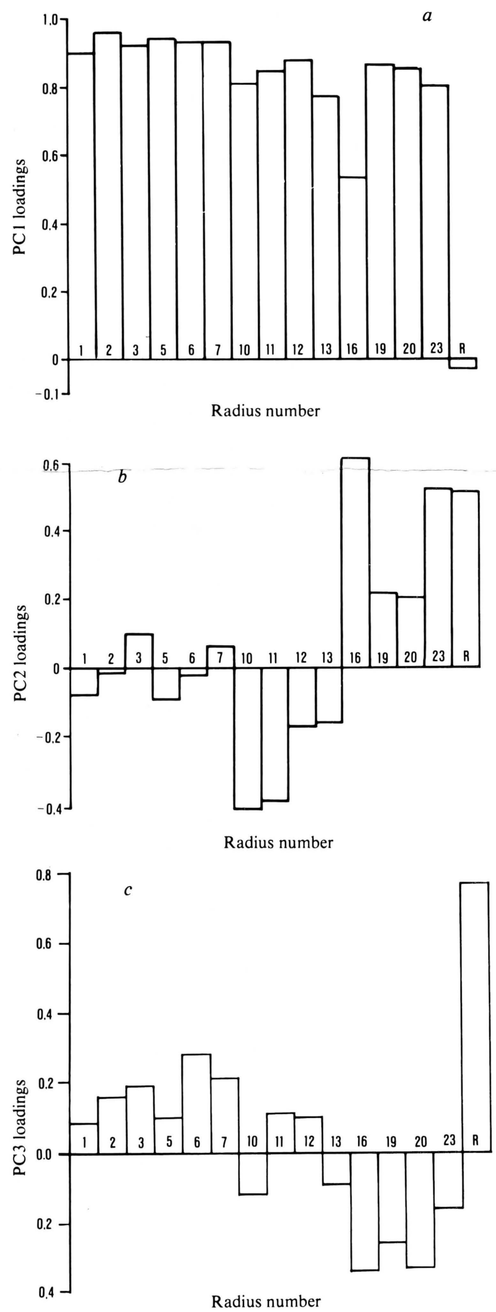

Fig. 2. *a*, The loadings of the first principal component, which give the correlations between each radius and rainfall with this component. Radii are indicated by numbers, and rainfall is noted as *R*. *b*, As in *a* but for the second principal component. In this case radii 10, 11, 16, 23 and rainfall *R* are represented by this component. *c*, The third component

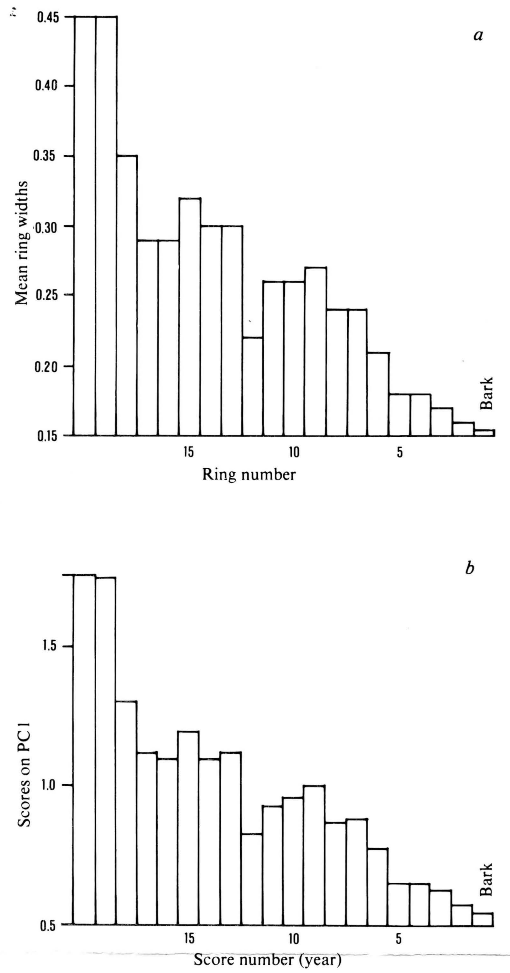

Fig. 3. *a*, The mean ring width per year over 14 radii. Ring 1 is outermost, *b*, This shows the scores on the first principal component. This is a time series and score 1 is the most recent. It clearly represents the mean variation in tree growth depicted in 3*a*.

Table 1. Showing the variances associated with each principal component together with the percentage and cumulative variances

PC	Variance	% Variance	Cum. var.
1	10.369	69.130	69.130
2	1.396	9.316	78.436
3	1.170	7.800	86.236
4	0.621	4.141	90.377
5	0.385	2.565	92.941
6	0.339	2.258	95.199
7	0.223	1.488	96.687
8	0.185	1.235	97.723
9	0.114	0.758	98.680
10	0.090	0.601	99.281
11	0.048	0.319	99.600
12	0.029	0.195	99.795
13	0.019	0.128	99.923
14	0.011	0.071	99.993
15	0.001	0.007	100.000

tree of much greater age one would therefore measure the rings back toward the pith, extending backwards beyond the length of existing rainfall records, and use these tree data to represent rainfall variation.

To evaluate the usefulness of principal components analysis to forestry science generally, this method was repeated using just the radial measurements as variables. In this case we worked with the covariance matrix, that is, we did not standardise the data matrix of ring widths, thus retaining the individual variation between radii. This time 91% of the total variance was accounted for by the first three principal components.

The mean ring width of all radii for each year is shown in Fig. 3*a*, and the scores for PC1 are given in Fig. 3*b*. A visual comparison of the two graphs suggests that PC1 represents the annual mean growth of the tree, which is confirmed by its correlation coefficient of 0.9. To investigate this aspect of growth one need therefore only consider the time series of scores on PC1.

The second principal component, PC2, is decidedly bi-polar, that is, the components form two blocks one of which is positive and the other negative (Fig. 4*a*). This represents a compensatory effect between the positively and negatively loaded radii on this principal component, which can be explained as follows. Radii 1 and 13 define the tension and compression axis (Fig. 1). Note that all the radii having negative PC2 coefficients are to the right of this axis, whereas all those with positive coefficients are to the left of it. Two large boughs grew out from the right-hand side of this portion of the tree. They measured approximately 11 cm in diameter compared with the maximum tree diameter of 40 cm. These boughs, which were cut off at the time the tree was felled, may have been the cause of the asymmetrical growth. Thus, when a ring on the right-hand side of the tree was putting down good wood, it did so at the expense of the same ring on the left-hand side, and vice versa. It is therefore possible that the effects of factors such as boughs, non-vertical growth, and prevailing cold winds, can be quantified by the technique described here.

The scores for PC2 established the effect of the growth of these boughs on tree growth. By comparing the graph in Fig. 4*b* with the photograph of the cross-section of one of the boughs, a possible interpretation suggests itself (Fig. 5). When the bough was putting down relatively large rings near its pith, the scores on PC2 were either negative or low. Conversely, when the bough ring-increments were small, the scores on PC2 were high (over rings 11 to 16). After this period, the bough ring-increments grew relatively large again and PC2 scores decreased.

PC1 and PC2 account for 87% of the total variation in ring widths. More subtle aspects of the growth are represented by PC3 and can be investigated in a similar way to that described for the first two components.

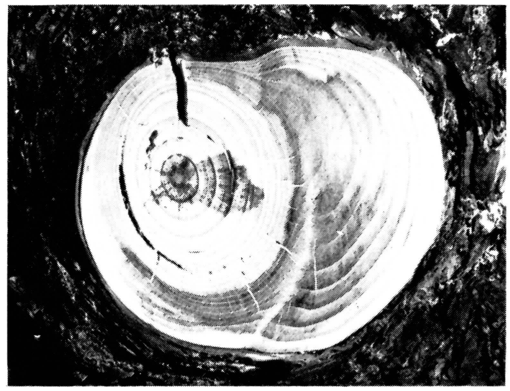

Fig. 5. This shows the variation in development of a bough and should be compared with Fig. 4*b*.

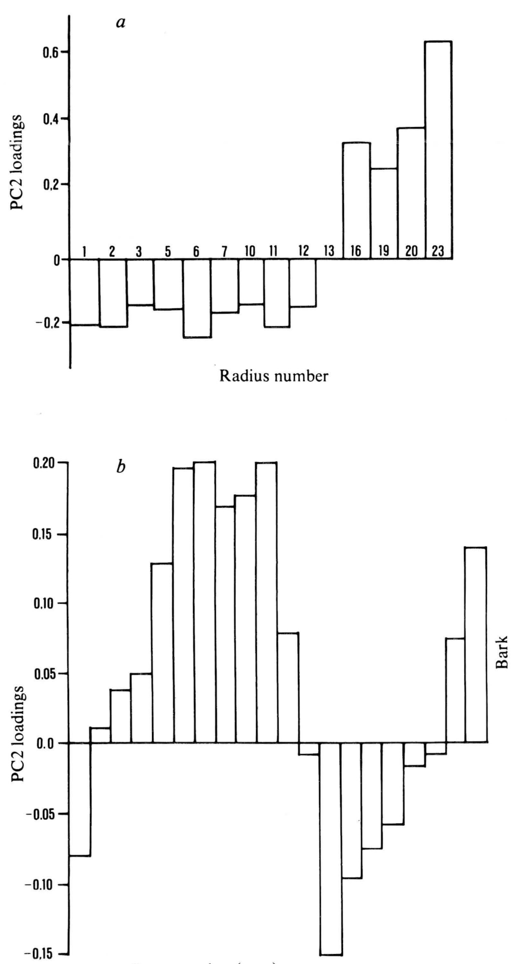

Fig. 4. *a*, The loadings here show the second principal component to be bi-polar. This component represents a compensatory effect between radii adjacent to and opposite to the free-growing boughs on the tree. *b*, This shows the temporal effect of the developing boughs on the cross-sectional growth of the tree. During a period of good ring-width formation (11 to 16),

Conclusions

We have shown that aspects of tree growth as represented by ring increments can be economically investigated using principal components analysis. Depending on the species and even the sample, particular PCs do not necessarily represent the same factors as those described here. However, it is likely that the first component would correspond to mean growth, and that others would indicate the idiosyncrasies of the specimen. It should be noted that although different tree-rings put down wood at different rates, this growth is not necessarily proportional to rainfall, otherwise we would not have found a PC that represented rainfall and only a few ring widths. In other words, we can study that growth which is different from the average from tree-ring widths not directly related to variations in rainfall.

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