THE USE OF X-RAY DENSITOMETRIC METHODS IN DENDROCHRONOLOGY

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INTRODUCTION

Dendrochronologists have traditionally relied primarily on the variations of ring-width in tree-ring sequences for purposes of crossdating and for paleoclimatic analysis. However, recent advances in techniques for measurement of wood density variations now provide a complementary method of tree-ring study.

Wood density is an integrated measure of several variable wood properties, including cell-wall thickness, lumen diameter, size and density of vessels or ducts, proportion of fibers, etc. It is possible to obtain continuous records of wood density by several non-mechanical methods. Photometry (Green and Worral 1964; Elliott and Brook 1967) and β-ray absorpiton (Phillips 1960) techniques are used with microscopic sections. Densitometric scanning of X-ray negatives (Polge 1966) offers the advantage that increment cores from living trees can be used with little further preparation.

This last method is also quick and sufficiently accurate to permit the critical evaluation of ring-density variations in a large number of samples in any particular study.

Several types of data can be obtained from the X-ray negatives. Of special interest are the maximum and minimum densities within each annual ring, and the rate of change of density between the earlywood and the latewood components. Density fluctuations within annual increments, such as those associated with intra-annual bands or "false" rings, can also be easily evaluated.

METHODOLOGY

The methodology may be summarized as follows:

Cores are taken with very well sharpened and cleaned borers, so that they are not distorted or damaged and so that the diameter is strictly uniform.

Cores which have not been extracted exactly following a perpendicular to the grain direction are propped adequately by gluing a piece of cardboard to obtain a clear image in spite of this obliquity.

Several cores (in general from 10 to 20) are X-rayed together using a tube with Beryllium-target and a low voltage both giving soft rays and therefore images with high contrast.

Now, in order that the optical density of the radiograph of a specimen can be used to study its wood density, it is necessary that there should be no other cause for changes in the optical density than the changes that actually occur in the wood density. This implies that the incident radiation should be uniform over the area containing the film, and that a given amount of radiation causes a given amount of film blackening.

Concerning the first requirement, a quite unusual source-film distance of 2.50m. is necessary to obtain a good uniformity of X-ray dose on all the film area since the corners of the film are further from the target than the centre, and since the intensity of the rays is inversely related to the third power of the distance from the source. In addition, we can have a clear image of all the rings (which are parallel to each other) only by using an approximately parallel X-ray beam obtained at the distance of 2.50 m.

The uniformity of blackening for a given dose received is only a problem of film development but it needs a meticulous care and particularly a continuous agitation of the developer.

The recording of optical density variations is made with a microdensitometer providing a high resolution and allowing an increase of the magnification of ring-width up to 50 times and also to change, when necessary, the scale of optical density.

When certain conditions are fulfilled (which cannot be detailed here) the optical density of the X-ray negatives is linearly and inversely related to wood density, so that microdensitometric records may be calibrated directly in wood density.

APPLICATIONS

FORMER RESULTS

In work previously reported (Polge 1966), it was shown that certain wood density parameters can be more characteristic of rings fromed in a given year than are the ring-widths themselves. In this work, samples from European plantations of *Abies grandis* and *Pseudotsuga menziesii* were studied. Each sample included 50 trees, and two 5 mm. increment cores (north and south sides respectively) from each tree. A total of 11 rings (representing the period 1953 - 1963) was analyzed from each radius. The results of a statistical analysis reproduced in Table 1 show that both the maximum latewood density and the difference between maximum density for one year and the minimum density for the following year are superior to the ring-width as a determinant of the year of formation of the annual ring.

Furthermore, a comparison with climatic records suggests that maximum density may be a sensitive indication of seasonal weather conditions. For the 11-year period of analysis, a coefficient of – 0.89 was obtained for the correlation of peak latewood density of *Pseudotsuga menziesii* with total precipitation for August, September and October. For the same period, peak density in *Abies grandis* gives a correlation of + 0.81 with the total duration of sunlight in July, August, and September.

FIRST DATING WORK USING DENSITOMETRIC PARAMETERS

In another study, the results of which are summarized here, wood-density variations served as the primary tool for crossdating of increment cores. This work, performed at the request of Th. Keller of the Federal Institute for Forest Research of Zurich (Birmensdorf), was concerned with the evaluation of damage to a stand of Norway spruce

Table 1. Variance Analysis

Characteristics	"F" test	
	Pseudotsuga menziesii	*Abies grandis*
Maximum annual density	79.07	71.83
Maximum density year n less minimum density year n + 1	57.13	80.76
Ringwidth	38.03	39.58
Minimum annual density	28.67	21.87
Percentage of latewood	16.36	13.51
Width of latewood	11.80	10.65

caused by heavy emission of industrial smoke during the last war. It was clear that a major effect of the smoke had been to reduce the width of several annual rings, and that in some cases the rings for the critical years were absent from the samples. The initial problem was thus to identify each of the annual rings in the samples from the damaged stand.

The approach which we followed was to analyze the density and ring-width characteristics from 25 trees in each of three stands: one heavily damaged (plot 1), one somewhat affected (plot 2), and another, unfortunately younger, which was unaffected and served as the control sample (plot 3). The period of analysis began in 1935, so that data were available for several years prior to the period of maximum industrial activity.

RESULTS

SHAPE OF DENSITOMETRIC RECORDS

The shape of the densitometric curve proved to be highly characteristic of rings formed in certain years, and provided a powerful dating tool. Examples are shown in Figure 1. The curves for 1935 typically show a rapid increase in density at the earlywood – latewood boundary, and often a bifurcated latewood peak. The 1939 and 1940 rings generally have very similar records. The ring for 1943 is one of the most characteristic rings for the plots 1 and 2, with a high minimum density and low maximum density. However, it is frequently absent, indicating the beginning of injury due to smoke. Yet it is quite normal from densitometric point of view for the plot 3. The ring for 1947 is also typified by high earlywood density followed by a low latewood density. However, it shows a more rapid density increase at the transition than does the 1943 ring and also the densitometric characteristics are the same for the plots 1 and 2 and for the plot 3. For 1960, the density maximum shows a double peak in most cases, of which the higher is often lower than the maximum densities in 1959 and 1961.

CHARACTERISTICS YEARS

The years, called "characteristics years", for which either the ring-width, or the maximum annual density or the minimum annual density have varied in the same direction (by comparison with the preceeding year) for at least 80 % of the total number

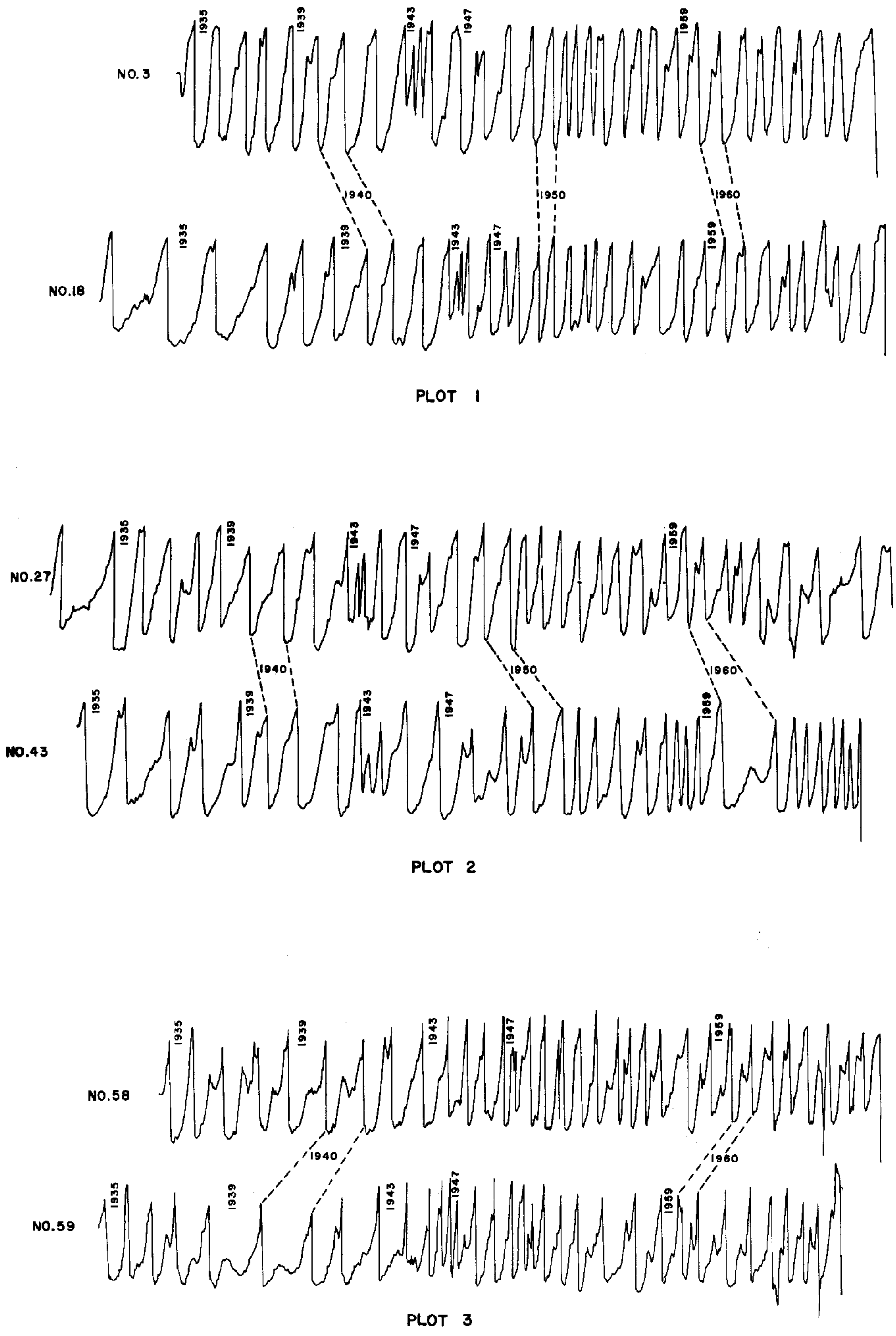


Fig. 1. Examples of Densitometric Records

Table 2. Number of Characteristic Years

	Plot 1	Plot 2	Plot 3	Total
Ringwidth	9	13	12	4
Maximum density	16	15	18	12
Minimum density	16	17	22	16

of trees, have been determined from densitometric records. The numbers of characteristic years are given in Table 2 for each plot separately and for the 75 trees of the 3 plots together.

We see that the homogeneity of results is very good for densitometric parameters, particularly when all the trees are considered together. In this case the number of "characteristic years" is three times higher for maximum density than for ring-width and four times higher for minimum density.

MEAN VALUES PER PLOT

The mean values of maximum density, minimum density and ring-width are shown in the Figure 2.

All the characteristics are similar between plots 1 and 2, but differ between both of them and plot 3. Ring-widths exhibit the greatest differences while the minimum densities exhibit the smallest differences.

The influence of the age of trees is very clear in plot 3 which has larger rings and lower maximum densities until about 1941. Then the stand apparently passed from the juvenile state to the adult one. After that the radial growth remains greater in plot 3 than in others plots, but the differences in maximum and minimum densities are very small.

There is a complete opposition between the curves of plots 1 and 2 and that of the plot 3 for ring 1943, with a larger ring a lower maximum density and a higher minimum density in the stand 3 than in the others. In 1947 the rings in all plots are similar. Thus the very low maximum density of 1943 is apparently due to the damages by industrial smoke, while that of 1947 is only related to climatic factors.

The variation coefficients (standard deviation reported to the mean values) are given in Table 3 for the 33 years of record. They confirm the larger variability of ring-width not only during the juvenile period but also for the rings near the bark.

CORRELATIONS BETWEEN THE MEAN VALUES OF THE PLOTS

Correlations between mean value of plots are given on the Table 4.

The correlation between the plots 1 and 2 is higher for the three criteria, leading to the conclusion that the both stands have been subjected to the same damages. Elsewhere in each comparison the density data show somewhat better mutual agreement than do the ring-width data.

The minimum density in particular appears as an excellent criterion for dating. It gives the highest correlation twice, and the coefficient for the third comparison is not very much lower than that of the maximum density. Thus it appears to be sensitive to climatic factors and not very sensitive to other causes of wood structure variation.

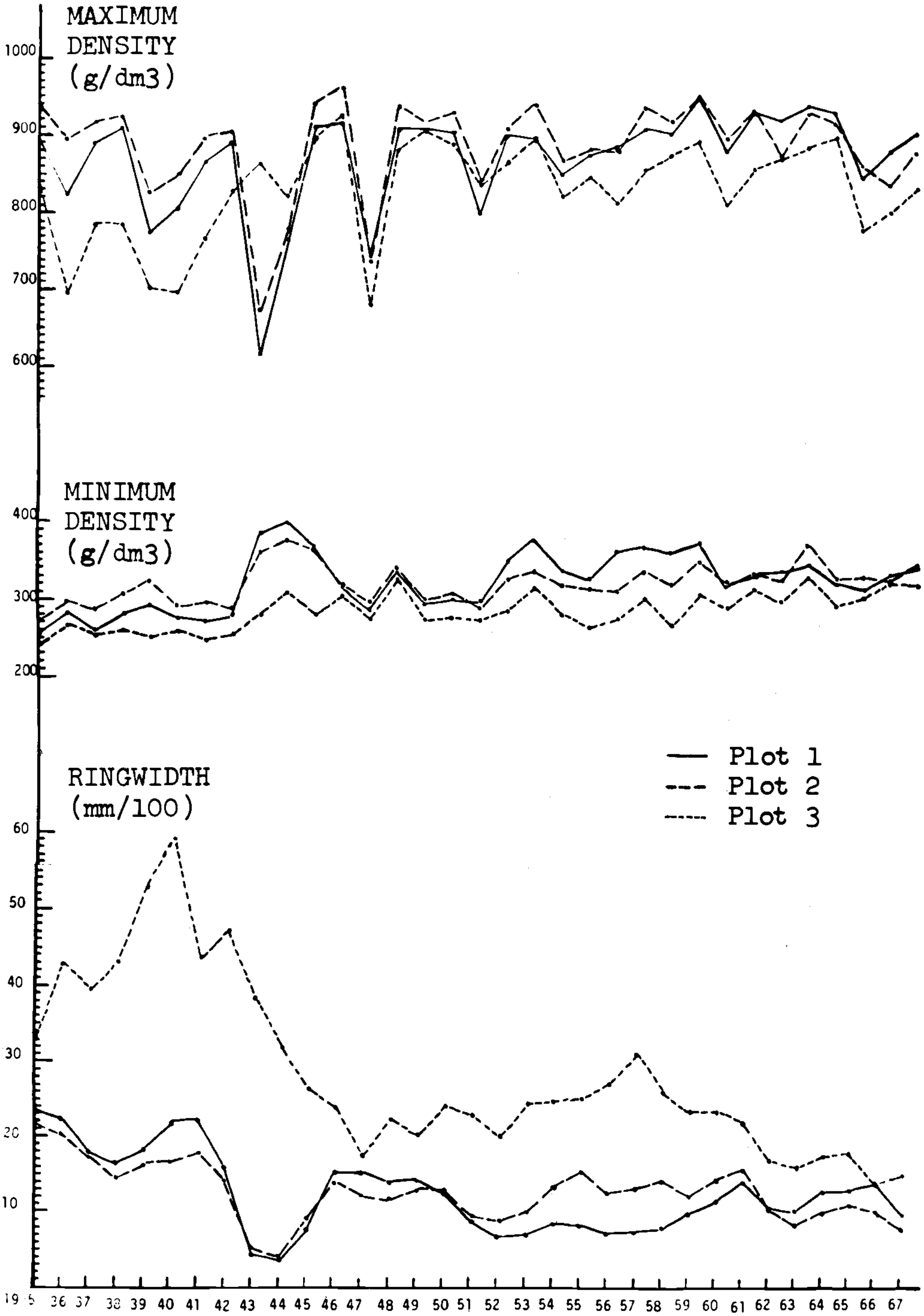


Fig. 2. Mean Annual Values per Plot

Table 3. Coefficient of Variation Between the Mean Values of the Plots

Years	Ringwidths	Maximum densities	Minimum densities
1935	23.07	5.99	6.06
1936	43.77	12.70	5.13
1937	51.12	7.98	7.25
1938	64.12	8.73	8.35
1939	69.84	8.19	12.70
1940	70.71	9.98	5.86
1941	48.33	7.99	8.92
1942	70.91	4.67	6.34
1943	117.38	18.05	15.90
1944	119.39	3.75	13.20
1945	69.94	2.59	15.37
1946	28.39	2.51	1.96
1947	16.16	4.95	4.23
1948	34.08	3.20	1.86
1949	24.14	0.73	4.69
1950	38.72	2.37	5.74
1951	54.91	3.02	4.21
1952	55.96	0.39	10.62
1953	63.49	2.86	9.28
1954	50.79	2.64	9.61
1955	49.96	2.24	11.60
1956	62.15	4.74	14.43
1957	68.12	4.69	11.05
1958	54.36	2.48	15.94
1959	45.96	3.63	10.35
1960	36.31	5.12	5.45
1961	22.65	4.87	3.76
1962	27.56	3.19	6.49
1963	32.79	3.33	6.66
1964	26.50	1.87	6.00
1965	24.10	5.41	4.39
1966	16.31	4.84	1.42
1967	33.00	4.25	4.56
Total	1614.99	163.95	259.38

CORRELATIONS BETWEEN CHARACTERISTICS

The correlation between ring-width, maximum density and minimum density are shown in Table 5.

The minimum density and ring-width are inversely correlated in all three cases. The maximum and minimum density are sometimes positively correlated. The maximum density and ring-width can be either positively or negatively correlated. Although the present data are inconclusive, it may develop that the time series of two or more ring-width or density parameters will commonly be found to be somewhat independant. This could provide a much stronger statistical basis for numerical cross-identification that is provided by ring-width data alone.

Table 4. Coefficients of Correlation Between the Mean Values of the Plots

	Ringwidths	Maximum densities	Minimum densities
Between plots 1 and 2	0.78**	0.91**	0.82**
Between plots 1 and 3	0.36^{NS}	0.49*	0.60**
Between plots 2 and 3	0.45*	0.46*	0.69**

* – Significant
** – Highly significant

Synthetic Xylochronologic Profiles

Synthetic Xylochronologic profiles (from the greek ξυλον = wood) are diagrams that record, for each year, in abcissa, the mean ring-width, and in ordinates, the mean maximum and minimum wood densities, and on which these extreme values of density are joined together by segments of straight lines.

Thus, details in the shape of densitometric records are not utilized. Yet these profiles make the work of wood dating very easy because they summarize the annual variations of two criteria instead of one in the usual ring-width chronology.

When some difficult problems of dating occur for a particular tree, a simple visual comparison of its synthetic profile with the mean profile of the correspounding plot generally allows a solution.

Example Of Synchronization

The densitometric record of tree 58 (see Fig. 1) shows eight apparent rings after the ring for 1960. Yet the sample had been gathered before the growing season of 1968. The dating up to 1960 was probably good because of the very characteristic shape of numerous rings. So a verification was necessary. We have compared the synthetic profile of this tree with the mean profile of the plot 3(Fig. 3).

On the mean profile of the plot the characteristic years for maximum and minimum densities (the definition of which is given above) are marked by a line slanting up or down as the correspounding parameter is significantly higher or lower than for the preceeding year.

On the profile of the tree 58 the same line is drawn when the parameter varies in the same direction as for the mean profile of the plot. A "O" means that the parameter varies in an opposite direction. We obtain a coincidence for 17 rings out of 18 from the point of view of maximum density, and 15 out of 18 for minumum density. Thus the dating seems right, since no change of the origin could give so much similarities of results.

Looking more carefully at the last rings, it appears that the dating of the rings 1962 and 1963 on the one hand and 1965 on the other hand are probably true, for it gives the same characteristic variations as the mean profile. This leads to the conclusion that the ring 1964 is represented on the densitometric record by something like two rings. In fact a more attentive examination of the radiography and of the sample itself reveals a very thin internal split in this ring, which gave an abnormal peak toward the low densities inside the latewood. Thus the appearance of an additional ring is explained.

Table 5. Coefficients of Correlation Between Characteristics

	Plot 1	Plot 2	Plot 3	Total
Between maximum density and minimum density	- 0.02	- 0.11	0.43*	0.22*
Between maximum density and ringwidth	0.09	0.40*	- 0.54**	- 0.36**
Between minimum density and ringwidth	- 0.87**	- 0.72**	- 0.64**	- 0.74**

* – Significant
** – Highly significant

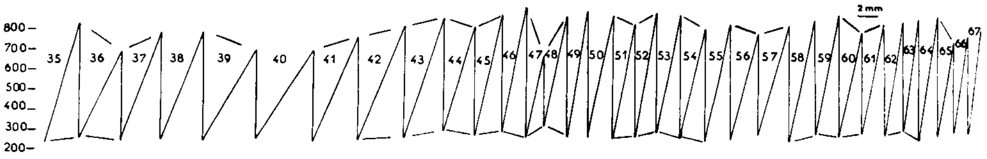
CONCLUSION

The densitometric records provide a way to measure objectively parameters other than ring-width and are not very closely related to ring-width. They can give additonal tool for wood dating.

Elsewhere these measures of density change less markedly with changes in tree age than do the ring-width. So there is often no need to remove growth functions when using density measurements.

Thus, together with ring-width, the densitometric parameters make cross-identification easier, quicker, and more accurate.

Plot 3 (mean values)



Tree 58 (plot 3)

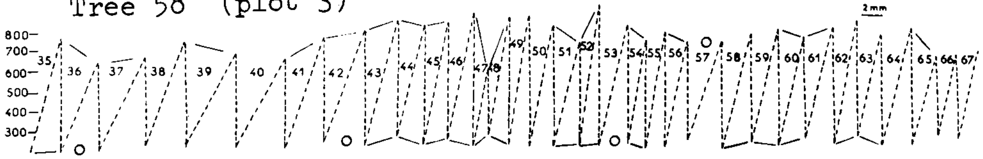


Fig. 3. Synthetic Xylochronologic Profiles

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