

PROVENANCE VARIATION IN WOOD CHARACTERISTICS OF
PINUS CARIBAEA MORELET AND P. OCCARPA SCHIEDE¹⁵

by

Jeffery Alan Wright

A thesis submitted for the degree of
Doctor of Philosophy at Oxford University

Hilary Term
1987



Green College
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Abstract

Densitometric, volumetric and paper-making traits of provenances of Pinus caribaea Morelet, P. oocarpa Schiede and P. patula Schiede and Deppe ssp. tecunumanii (Eguiluz and Perry) Styles were evaluated. Provenance mean values of densitometric density (DEN) and within tree density variation (VAR) were significantly different ($p < 0.05$) at seven of the fourteen P. caribaea and at one of the seven of P. oocarpa and P. patula ssp. tecunumanii trials. Provenance mean values of volume under bark (VUB) and dry matter index (DMI) were significantly ($p < 0.05$) different at all of the P. caribaea and at five of the P. oocarpa and P. patula ssp. tecunumanii trials. The inland provenances of P. caribaea were generally higher for DEN and VAR than the coastal provenances. The Camelias, Mountain Pine Ridge, Rafael and Yucul provenances of P. patula ssp. tecunumanii were superior to P. oocarpa provenances for VUB and DMI in all of these trials and were superior to P. caribaea at two sites where the species were growing under similar conditions. Evaluation of densitometric traces revealed large differences between species, provenances and sites for the width and density of latewood; this could explain much of the variation in VAR between these sources.

The analysis of variance was used to assess genotype by environment interaction of DEN and VAR from eleven provenances of P. caribaea var. hondurensis Barrett and Golfari at eleven sites and from five provenances of P. oocarpa and four provenances of P. patula ssp. tecunumanii at six sites. Sites and provenances were significantly different for DEN and VAR in both series of trials but the site by provenance term was not statistically significant in either. Indications were that P. caribaea would be expected to have lower values of DEN and VAR at higher altitude. Provenances of P. oocarpa and P. patula ssp. tecunumanii were lower for VAR at sites of lower latitude but there were no individual site factors which could be correlated with DEN in these provenances.

The comparison of full-scale pulping with micropulping of small wood samples from felled trees of six pine species in the Eastern Transvaal, South Africa, revealed positive and significant correlations for the pulp yield and paper strength traits. The correlation of tear index and VAR in these trees was positive and significant. Evaluation and analyses of a number of pine species and provenances by micropulping of cores from standing trees revealed significant differences for certain of the paper strength traits. The Cañas provenance of P. oocarpa was unusual in having high values for both tear index and burst index when grown in Zululand. Similar conclusions were reached for provenances of P. patula ssp. tecunumanii grown in the Eastern Transvaal.

The conclusions of this thesis were:

1. Site climatic factors did not affect DEN and VAR of the different species and provenances in the same way
2. The VAR term varied as a result of site, species and provenance
3. There was no genotype by environment interaction for DEN and VAR
4. The correlation of VAR with pulp and paper-making traits indicated that trees with high VAR were superior for tear index to trees with low VAR
5. Micropulping of small wood samples could be used to assess the paper-making traits of individual trees.

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1. INTRODUCTION

1.1 Tropical pines as plantation species

Two of the most important conifer species for planting in the tropics and subtropics are Pinus caribaea Morelet and Pinus oocarpa Schiede. Large plantation schemes with P. caribaea are found in Australia, Brazil, Congo, Fiji and Venezuela while large scale afforestation with P. oocarpa is at present limited to Brazil. Provenance trials of these species coordinated and assessed by organizations such as the Oxford Forestry Institute (OFI), University of Oxford, have shown a conservative 30% increase in productivity due to proper seed source selection (Plumptre and Barnes, 1982). These authors have concluded that the increase in value through the use of proper seed source of P. caribaea and P. oocarpa could exceed one billion dollars per annum by the year 2000.

While the gains from provenance testing and selection for volume and form traits have in many cases exceeded initial expectations, there has been less emphasis placed on selection for wood quality. One result is that the products manufactured from the wood grown in these vigorous and healthy plantations may not meet the minimum required strength and quality requirements (Zobel, 1986). In Brazil, for example, it was concluded that structural failures would result from the use of lumber derived from plantations of thinned trees of P. caribaea (Bower et al., 1976). At least one paper manufacturer in South Africa will take only a small percentage of P. caribaea as mill furnish due to the low tear factor of paper made from that species. The hypothesis that tree breeders can concentrate selection and breeding on volume and form is thus not always correct especially when growing exotic species in plantations. The problem of selecting and breeding for wood density is that industrial organizations are often hesitant to specify the wood density desirable for their end product. Any organization that intends to be competitive in

the international market for forest products must be concerned with wood quality and its effect on their end product (Zobel, 1986).

The term wood quality as used in this thesis will primarily concern the density and variation of density of wood. Wood density can be assessed using gravimetric or densitometric methods and numerous methods have been developed to detect variation of density (Kanowski, 1985). Wood quality is known to affect most end uses of wood but there is often disagreement as to its economic weighting or even inclusion in a selection index. Also, wood density does not account for all of the variation in an end product (van Buijtenen, 1969) and for this reason some organizations have developed other methods of assessing the wood of superior phenotypic sources. One possible method for assessing papermaking traits involves pulping small quantities of wood and testing the sheets made from the resulting pulp (Palmer, 1985). Micropulping of small wood samples in this manner could become an integral part of tree breeding and silvicultural management in the future.

1.2 Review of literature concerning wood quality

Environmental and genotypic effects

Wood density in the conifers normally increases as one moves out from the centre of a tree and decreases as one moves up the tree. In temperate conifers, the dates of flushing and cessation of growth have been found to be of importance in determining wood density. Mergen et al. (1964) found in Picea abies (L.) Karst. that trees which flushed early had a higher percentage of earlywood and thus a lower density than trees that flushed later. In P. banksiana Lamb., Kennedy (1971) observed that trees which initiated latewood formation at an earlier date had a higher percentage of latewood. Flushing and cessation of cambial growth can affect wood density through growth substances produced in the

foliage and/or the apical meristem. These growth substances are then transported to the cambium where they affect processes controlling cell wall formation (Larson, 1962a; Wareing et al., 1964).

In tropical and temperate climates numerous studies have shown that moisture stress is of major importance in determining wood density. Slee and Nikles (1968) observed that trees of P. caribaea var. hondurensis showed a marked increase in latewood percentage and a trend of increasing basic density in coastal plantations from southern to northern Queensland. They concluded that these trends could be the result of increasing soil moisture deficit from southern to northern Queensland. In Puerto Rico, Geary and Macia (1973) found that wood density of P. caribaea was higher on sites with longer periods of soil moisture deficits. Wood density of P. caribaea in Queensland was significantly ($p < .05$) and positively correlated with average annual figures for potential evapotranspiration, evaporation and accumulated potential water loss (Smith, 1973). In a study of six-year old P. caribaea provenance trials in Zimbabwe, Barnes et al. (1977) concluded that wood density seemed to increase as moisture stress increased. Harris et al. (1978) in a study of clonal P. radiata D. Don found that earlywood density and mean density were highest when there were year round soil moisture deficits. Soil moisture deficits are influenced by soil type and rainfall and can influence wood density by affecting growth substances in the cambium (Larson, 1962a; Whitmore and Zahner, 1966).

Silvicultural techniques can greatly affect wood density. Fertilization has been shown to decrease wood density in P. radiata (Harris et al., 1978), Pseudotsuga menziesii (Mirb.) Franco (Erickson and Lambert, 1958) and P. elliotii Engelm. (Williams and Hamilton, 1961). Heavy thinning at age 16 years was observed in P. kesiya Royle ex Gordon to result in significantly lower wood density relative to unthinned or lightly thinned plots

(Burley, 1970). Fertilization and thinning often result in increased earlywood formation which is normally lower in density than latewood (Larson, 1962b). Pruning can lead to increased wood density as was found by Plumptre (1979) in P. patula Schiede and Deppe in Uganda. In that study, severe pruning done before the trees were 3.5m tall was found to increase significantly the central core wood density in the bottom log of the tree.

The effect of genotype on wood density can be readily assessed by sampling the species, provenances or clones in question. Some studies have shown little genetic control of density as with P. caribaea provenances in Thailand (Granhof, 1980) and Pseudotsuga menziesii provenances in the Pacific Northwest of North America (Cown and Parker, 1979). However, most genetic sources of trees do differ from each other in their wood density. To cite all of the studies which have shown significant differences in wood density between sources would be an exhaustive task and only some of the most relevant sources will be cited here. Posey et al. (1970) observed significant ($p < .05$) differences in wood density between provenances of P. echinata Mill. as did Echols (1958) with provenances of P. sylvestris L. ($p < .01$). In P. caribaea, Barnes et al. (1983) noted that provenances from coastal areas had consistently lower density than either the more inland sources or the insular source, Guanaja. Falkenhagen (1979) has also found significant differences in wood density of P. caribaea provenances in South Africa. Burley (1976) has given a more detailed description of the genetic variation in wood properties.

Studies on the heritabilities of wood density have shown a large degree of genetic control. Stonecypher and Zobel (1966) found a heritability of 0.73 for unextracted wood density in a five-year-old open pollinated trial of P. taeda L. In clones of P. radiata, the heritability of mean density was found to vary from 0.60 near the pith to 0.24 at the ninth growth ring and to increase to 0.60 with increasing age (Nicholls, 1967). In P. caribaea, Kanowski (1986) estimated the broad sense heritability

for densitometric density on an individual tree basis at age ten years to be 0.90 in P. caribaea. High heritabilities such as these indicate the potential effectiveness of selection and breeding for improvements in wood density.

The wood density of a genetic source can vary as a result of environment. For instance, Barnes et al. (1977) observed that P. caribaea provenances were lower in density at higher altitude and this was possibly due to greater moisture stress at lower altitude. The gravimetric density of provenances of P. caribaea growing across a number of sites were found to differ significantly between sites ($p < 0.001$) but provenances within a site were not found to differ significantly (Barnes et al., 1983). The results of these studies indicate that phenotype will differ depending upon the environment and this is not surprising given the large soil and climatic differences between sites. It also indicates that a genetic source with adequate wood density at one location may not have sufficient wood density when planted at a second site. Burdon (1977) has cautioned that tree breeders must give more attention to environment rather than genotype in generating genotype by environment interactions and the results of studies in wood density would seem to confirm this.

The effect of wood density on papermaking traits

Several studies have shown wood density to be the most important wood property affecting pulp yield and many tree breeding programmes include density in their selection criteria. Burley and Palmer (1979) found that total pulp yield in P. caribaea var. hondurensis Barr. and Golf. growing in Fiji was significantly correlated with unextracted mean density ($r = .603$). In a study of P. taeda L., Barefoot et al. (1970) concluded that total paper yield was more related to the percentage of latewood than to density. The different conclusions reached in these two studies could be due to the frequent absence of latewood in P. caribaea var. hondurensis grown in the tropics.

Density can also influence the paper strength properties of tear index, burst factor, breaking length and tensile strength. In P. radiata, Corson (1984) observed that trees with high density gave paper with higher tear index but lower tensile strength. In Fiji-grown P. caribaea, Ong (1978) found that tear factor was higher for trees of higher density and a similar conclusion was reached by Barefoot et al. (1966) for P. taeda. Kibblewhite (1984) in a study of P. radiata trees grown in New Zealand observed that chip basic density accounted for 81.0, 79.0 and 62.1 percent of the variation of, respectively, tear index, burst factor and tensile strength. That study also found that as chip density increased burst factor and tensile strength decreased while tear factor increased. Burley and Palmer (1979) also found a significant and positive correlation of tear factor and wood density of Fiji-grown P. caribaea as well as a significant and negative correlation of breaking length and burst factor with wood density. The influence of wood density on paper strength traits allowed Namkoong et al. (1969) to conclude that selection and breeding for wood density would have an effect on paper properties. However, selection for high wood density may result in increased tear index but could decrease burst factor, breaking length and tensile strength (Palmer, 1986).

An organization must know those paper strength properties most critical for its products before selecting for high or low wood density. For instance, van Buijtenen (1987) used a computer to simulate the effects of rotation age and tree improvement on multiwall sack paper and found that the model would decrease rotation age as far as possible until the critical specific gravity of 0.45 was reached. His conclusion was that wood specific gravity was the critical factor and could not be reduced below 0.45.

1.3 The provenance trials

The provenance trials assessed in this thesis represent a wide variation in altitude and latitude and hence large differences in rainfall and temperature patterns exist between sites. The experimental details of the trials are contained in Table 1.1 and environmental details are summarized in Table 1.2. Gibson (1982) collected the wood samples assessed in the densitometric portion of this thesis as part of the International Provenance Trials, Intensive Assessment Schedule (I.P.T., I.A.S.). The seed for these trials were collected and distributed under Research Schemes at the OFI with funding from the Overseas Development Administration (ODA) of the British Government. The intention of the I.P.T., I.A.S., was to determine the extent and nature of genotype by environment interaction (GEI) as well as to evaluate provenance performance for quantitative and qualitative growth traits (Gibson, 1982). The intention of this thesis is to make similar determinations for densitometric traits from fourteen trials of P. caribaea and seven trials of P. oocarpa and for pulping and papermaking traits from two trials of P. caribaea and two trials of P. oocarpa in South Africa. Of special interest are the locations where trials of the two species are growing under similar environmental conditions. This allows for a comparison of the densitometric and volumetric traits of the two species.

Certain of the P. caribaea trials include provenances of P. caribaea var. bahamensis Barr. and Golf. and P. caribaea var. caribaea Morelet but for the GEI analysis only provenances of P. caribaea var. hondurensis were included. The reason for this is that provenances of P. caribaea var. bahamensis and P. caribaea var. caribaea were not present in enough trials to warrant their inclusion in the overall analysis. Also, these varieties do not have the proven volume potential of P. caribaea var. hondurensis. Provenance details of P. caribaea are summarized in Table 1.3.

Greaves (1978) and Robbins and Hughes (1983) discussed in greater detail the P. caribaea provenances assessed in this thesis.

Table 1.1 Details of experimental design of P. caribaea and P. oocarpa provenance trials.

Location	No. of Blocks	Overall plot size	Measured plot size	Trees sampled /measured plot	Spacing (m)
<u>P. caribaea</u>					
Anasco-A, Puerto Rico	5	7x1	7x1	2	2.7x2.7
Anasco-B, Puerto Rico	5	7x1	7x1	1	2.7x2.7
Chati, Zambia	4	10x10	4x4	3	3.0x3.0
Loudima, Congo	5	6x6	4x4	3	2.5x2.5
San Pedro, Ivory Coast	5	10x6	4x4	3	4.0x2.0
Mariti, South Africa	5	6x6	4x4	3	2.7x2.7
KwaMbonambi, South Africa	5	6x6	4x4	3	2.7x2.7
Bukit Tapah, Malaysia	3	6x6	4x4	3	2.5x2.5
Drasa, Fiji	10	5x1	5x1	1	3.0x3.0
Nanuku, Fiji	10	5x1	5x1	1	3.0x3.0
Beerburrum, Australia	5	10x1	10x1	3	3.0x3.0
Byfield, Australia	5	7x7	4x4	3	2.4x2.7
Cardwell, Australia	5	7x7	4x4	3	2.7x2.5
Jari, Brazil	5	7x7	4x4	3	3.0x3.0
<u>P. oocarpa</u>					
Anasco, Puerto Rico	5	7x1	7x1	2	2.7x2.7
Conocoto, Ecuador	5	7x7	4x4	3	2.0x2.0
Agudos, Brazil	4	5x5	4x4	3	3.0x3.0
Ndola East, Zambia	2	10x6	8x2	3	3.1x3.1
Wilgeboom, South Africa	5	6x6	4x4	3	2.7x2.7
KwaMbonambi, South Africa	5	6x6	4x4	3	2.7x2.7
Nzoia, Kenya	4	5x5	4x4	3	2.5x2.5

Table 1.2 Details of environmental conditions of P. caribaea and P. oocarpa provenance trials.

Location	Lat. (°)	Alt. (m)	Mean Annual Precip. (mm)	Mean Annual Temp. (°C)	Age (months)
<u>P. caribaea</u>					
Anasco-A, Puerto Rico	18.33 N	175	2090	25.3	69
Anasco-B, Puerto Rico	18.33 N	175	2090	25.3	69
Chati, Zambia	13.00 S	1300	1273	20.5	86
Loudima, Congo	4.21 S	150	882	24.6	100
San Pedro, Ivory Coast	4.75 N	20	1900	26.0	105
Mariti, South Africa	24.90 S	1000	1556	17.3	75
KwaMbonambi, South Africa	28.75 S	65	1338	22.0	86
Bukit Tapah, Malaysia	4.33 N	549	3334	24.3	66
Drasa, Fiji	17.58 S	35	2335	25.5	84
Nanuku, Fiji	17.98 S	230	3119	22.0	86
Beerburrum, Australia	27.00 S	12	1546	20.8	72
Byfield, Australia	22.83 S	30	1745	21.8	73
Cardwell, Australia	18.27 S	20	2127	24.1	72
Jari, Brazil	0.87 S	76	2200	26.5	75
<u>P. oocarpa</u>					
Anasco, Puerto Rico	18.33 N	175	2090	25.3	69
Conocoto, Ecuador	0.26 N	2510	1386	15.2	72
Agudos, Brazil	22.37 S	550	1300	21.2	84
Ndola East, Zambia	13.00 S	1300	1174	19.6	75
Wilgeboom, South Africa	24.97 S	945	1348	18.2	91
KwaMbonambi, South Africa	28.75 S	65	1338	22.0	86
Nzoia, Kenya	0.93 N	1700	1250	18.9	91

It has been noticed by numerous researchers that there are good reasons why provenances of P. caribaea var. hondurensis could be

separated into inland and coastal groups. The basis of this grouping is on phenotypic performance rather than taxonomic differences. For this thesis, the P. caribaea var. hondurensis provenances from an altitude of 400m or greater will be referred to as inland and the remaining provenances will be referred to as coastal. The Byfield provenance will be included in the inland group since this source was derived from the inland provenance Mountain Pine Ridge.

The reclassification of four of the P. oocarpa provenances assessed in this thesis to P. patula Schiede and Deppe ssp. tecunumanii (Eguiluz and Perry) Styles has been discussed elsewhere (Barnes and Styles, 1983; Styles, 1985; and McCarter and Birks, 1985). The volume productivity of P. patula ssp. tecunumanii provenances exceeded that of P. oocarpa provenances at many of the trials in this assessment and there is interest in selection and breeding of this species by numerous organizations (Ladrach, 1986). In this thesis, however, these trials will be generally referred to as P. oocarpa. Provenance details of P. oocarpa are summarized in Table 1.4. Greaves (1979) and Robbins and Hughes (1983) discussed in greater detail the P. oocarpa provenances assessed in this thesis.

Certain of the provenance trials contain sources of different origin to the provenances in question. Some of these genetic sources have undergone selection and breeding and were included as a control as was the case with P. elliottii at the four trials in South Africa. The Byfield source of P. caribaea var. hondurensis was included in many of the trials and has been included in the GEI analysis. Seed of the Byfield source was supplied by the Queensland Forestry Department from the 127B clone bank at Byfield, Queensland, Australia. The selections comprising the Byfield source were based on volume and form and were made in plantations derived from Mountain Pine Ridge, Belize (Nikles and Spidy, 1973). Inclusion of improved material such as Byfield give the tree breeder and plantation manager an idea of

the potential of P. caribaea given one cycle of selection and breeding.

Table 1.3 Details of P. caribaea provenances (Greaves, 1978).

Variety	Provenance	Code	Lat. (°)	Alt. (m)	Mean Annual Precip. (mm)	Mean Annual Temp. (°C)
var. <u>bahamensis</u>	Andros Island	AND	24.88 N	3	1055	25.4
var. <u>caribaea</u>	Batey	BTY	22.83 N	-	-	-
	Buren	BUR	22.75 N	300	-	-
	Cabanas	CAB	22.67 N	160	-	-
	Caya la Mula	CAY	22.55 N	110	-	-
	Manuel	MAN	22.62 N	150	-	-
	Marbajita	MAB	22.80 N	80	-	-
	Palacios	PCC	22.57 N	50	-	-
	Pinar	PIN	22.82 N	-	-	-
	Vifiales	VIN	- N	-	-	-
var. <u>hondurensis</u>	Alamicamba	ALA	13.57 N	20	2610	27.3
	Briones	BRI	15.57 N	600	912	24.0
	Brus Lagoon	BRU	15.75 N	10	2840	26.5
	Byfield	BYF	22.83 S	10	1820	21.6
	Culmi	CUL	15.10 N	600	1325	24.3
	Futululu	FUTC	28.75 S	7	1338	22.0
	Guanaja	GUA	16.47 N	50	2308	27.1
	Karawala	KAR	12.97 N	10	3897	26.4
	Kuakil	KUA	14.20 N	20	3208	26.5
	Kuakil(A)	KUA(A)	-	-	-	-
	Limones	LIM	14.05 N	700	663	22.2
	Melinda	MEL	17.02 N	10	2137	26.9
	Mountain Pine Ridge	MPR	17.00 N	400	1558	23.9
	Poptun	POP	16.33 N	500	1688	24.2
	Poptun(nonOFI)	POP(A)	-	-	-	-
	Potosi	POT	15.33 N	600	1205	23.7
	Rio Coco	RIO	14.75 N	50	2863	25.8
	Santa Clara	STA	13.92 N	700	1818	23.4
	Santos	SAN	17.57 N	20	1818	26.2
	130R	130R	22.83 S	10	1820	21.6
	¹ <u>P. elliotii</u>	PEL1				
	² <u>P. elliotii</u>	PEL2				

¹ Seed orchard control, South Africa

² Commercial control, South Africa

Table 1.4 Details of P. oocarpa and P. patula ssp. tecunumanii provenances (Greaves, 1979).

Species		Code	Lat. (°)		Alt. (m)	Mean Annual Precip. (mm)	Mean Annual Temp. (°C)
<u>P. oocarpa</u>	Agua Fria	FRI	15.27	N	1100	1069	21.6
	Angeles	ANG	14.17	N	1300	920	20.2
	Bonete	BON	12.83	N	950	922	21.4
	Bucaral	BUC	15.02	N	1000	900	21.6
	Cañas	CAN	15.17	N	1200	1900	21.3
	Chuacus	CHA	15.03	N	1300	790	22.5
	Conacaste	CON	15.17	N	550	1900	24.6
	Dola Hill	DOL	13.00	S	1300	1273	20.5
	Futululu	FUTO	28.75	S	7	1338	22.0
	Huehuetenango	HUE	15.32	N	1700	1037	16.9
	Jitotol	JIT	17.00	N	1000	-	-
	Junquillo	JUN	13.70	N	1000	904	21.8
	Lagunilla	LAG	14.70	N	1600	936	19.5
	Lima	LIM	15.18	N	1000	1800	22.4
	Maraquito	MAR	14.22	N	1000	1272	21.8
	Pueblo Caido	PUE	15.20	N	800	1900	23.5
	San Jose	JOS	14.47	N	1000	956	22.4
	San Marcos	SAM	14.60	N	1100	1272	21.3
	Siguatepeque	SIG	14.53	N	1100	1247	19.9
	Zamorano	ZAM	14.03	N	1100	1117	20.2
Zapotillo	ZAP	14.62	N	1000	1272	21.8	
<u>P. patula</u> ssp. <u>tecunumanii</u>	Camelias	CAM	13.77	N	900	1500	22.4
	Mountain Pine Ridge	MPO	16.97	N	700	1558	23.9
	Rafael	RAF	13.23	N	1200	1366	20.8
	Yucul	YUC	12.92	N	900	1394	22.4

¹P. elliottii PEL1
²P. elliottii PEL2

¹Seed orchard control, South Africa

²Commercial control, South Africa

1.4 Description of sampling and densitometric procedures

The trials were evaluated in 1979, 1980 or 1981. The number of trees sampled for density varies from one to three per measurement plot. This sub-sample is likely to contain the final crop trees and those most likely to be included in any future

breeding population. At the time of measurement, increment cores of 8mm diameter were removed bark to bark at breast height (1.3m) from the largest diameter tree(s) in the measurement plot. Following shipment to the OFI, the cores were oven-dried to 12 percent moisture content, weighed and the gravimetric density determined using dry weight and wet volume calculated from nominal 8mm increment core diameter and fresh core length (Barnes et al., 1983). The cores were then machined to 5mm thickness in both axial and radial planes and the resin was extracted with a solvent of one part ethyl alcohol and two parts benzene by refluxing in a Soxhlet condenser for 24 hours.

Hughes and Sardinha (1975) and Kanowski (1985) have described in detail the equipment and procedures used at the OFI with respect to densitometry. The machined increment cores were X-rayed and the resulting radiographs were scanned using the Joyce-Loebl MDM6 optical densitometer. The resulting data were used to calculate the mean densitometric density (DEN) as well as the within sample density variation (VAR). The VAR term is derived identically to the standard deviation but does not have its statistical connotations. The lower the value of VAR the greater the wood uniformity.

In addition to the densitometric traits, data are also presented for volume under bark (VUB) and dry matter index (DMI). The VUB was determined for each tree sampled for DEN using under bark diameter at breast height, total height and a form quotient based on the outside bark diameter at breast height and at 6m (Gibson et al., 1983). The DMI term is the product of DEN and VUB. The VUB production of P. caribaea provenances has been discussed by these authors as well as Gibson (1982). The VUB and DMI values are included in this thesis to indicate the production potential of these genetic sources and to indicate whether fast growth results in wood of lower density. These terms will not be covered in the same detail as DEN and VAR.

2. ASSESSMENT OF INDIVIDUAL TRIALS

The data for DEN and VAR were analyzed using a randomized complete block design with provenances as fixed effects and blocks as random effects. For individual trials the model used was:

$$\text{DEN}_{b_p} \text{ or } \text{VAR}_{b_p} = \mu + B_b + P_p + E_{b_p}$$

where DEN_{b_p} or VAR_{b_p} is the value of the b^{th} block and the p^{th} provenance, μ is the population mean, B_b is the effect of the b^{th} block, P_p is the effect of the p^{th} provenance and E_{b_p} is the residual. The form of the analysis of variance (ANOVA) and the expectation of mean squares are given in Table 2.1. The data for DEN and VAR had units in g cm^{-3} but the data presented in the figures for these traits has units in kg m^{-3} . The standard errors were also calculated in these units. Data for VUB and DMI were also analyzed using ANOVA but have not been discussed in great detail.

Table 2.1 Analysis of variance and expectation of mean squares for individual trials.

Source	df	Expectation of mean squares
Provenances	$p-1$	$\sigma_e^2 + b\sigma_p^2$
Blocks	$b-1$	$\sigma_e^2 + p\sigma_b^2$
Residual	$(p-1)(b-1)$	σ_e^2
Total	$pb-1$	

2.1 P. caribaea trials

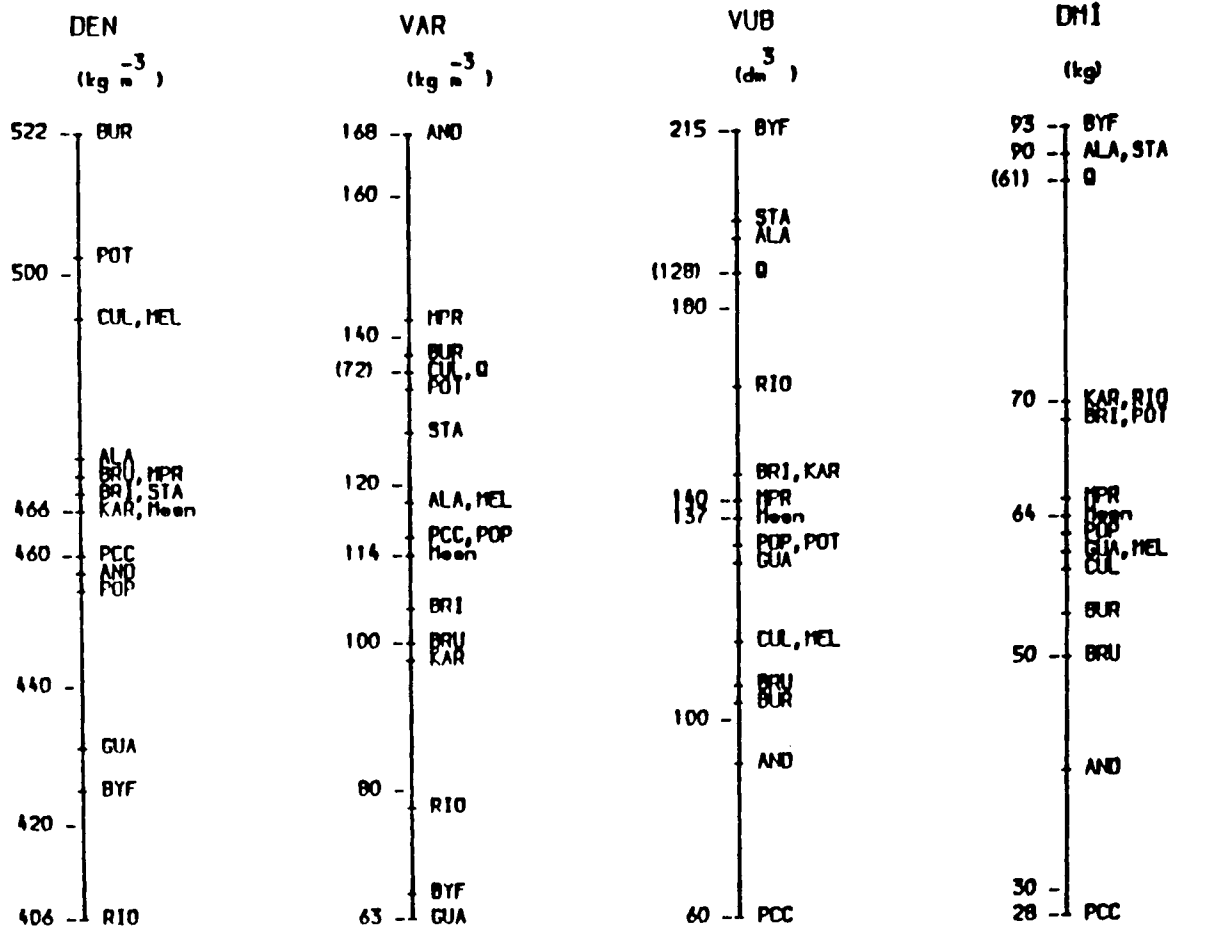
Anasco, Puerto Rico

The two adjacent trials at Anasco are further North than any

other trial. In the Anasco-A trial, there were 13 provenances of P. caribaea var hondurensis, one provenance of var. bahamensis and two provenances of var. caribaea. There were two provenances of var. caribaea and thirteen of var. hondurensis at the Anasco-B trial. These trials have been reported on by Gibson (1982), Liegel et al. (1983) and Liegel (1984a).

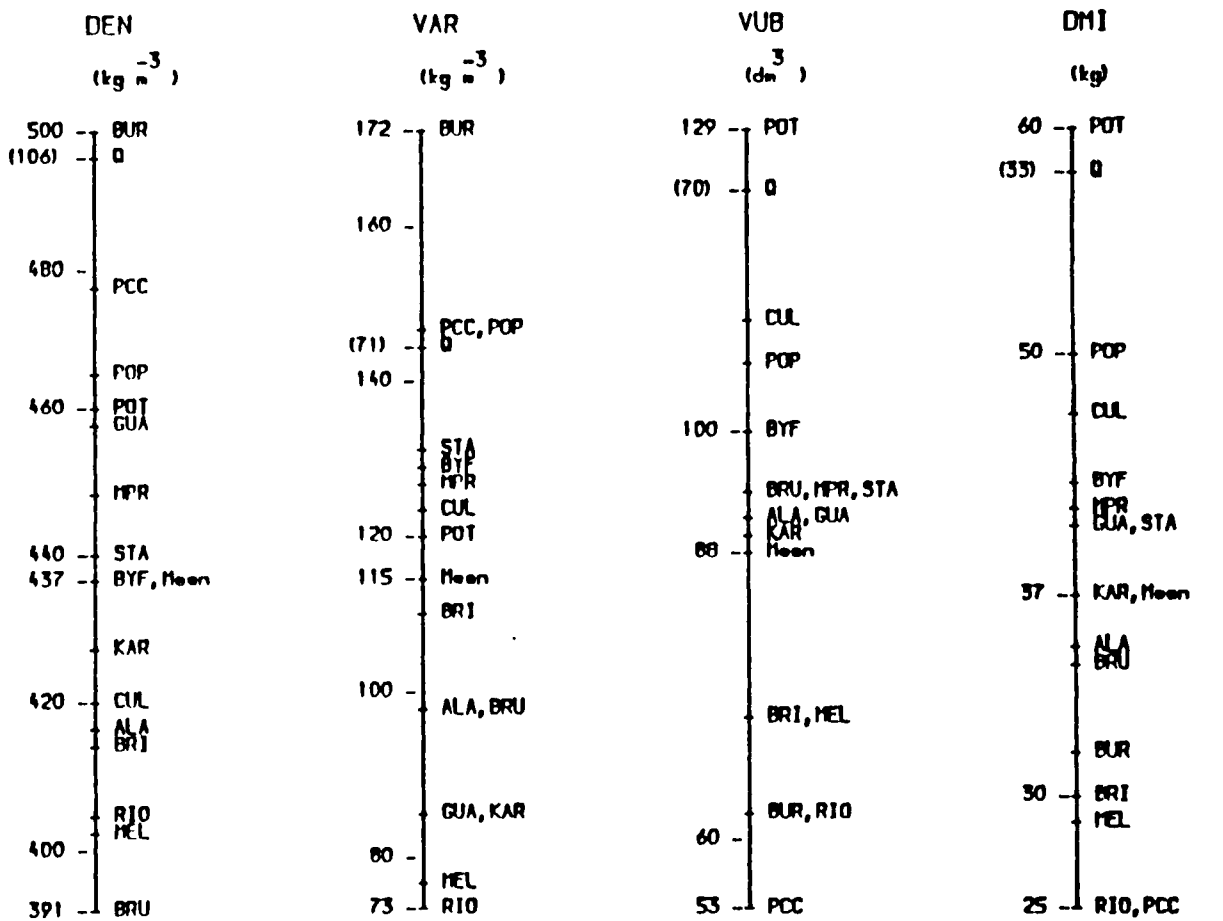
The results of the ANOVA are reported in Figure 2.1 for Anasco-A and in Figure 2.2 for Anasco-B. The partial ANOVA table is contained in Table 2.2. Provenances were significantly different for VAR ($p < 0.001$) in both trials and for DEN ($p = 0.021$) at Anasco-B. Provenances were not significantly different for DEN at Anasco-A and the Q statistic has been omitted for this trait in that trial. The coastal provenances of var. hondurensis, Karawala and Rio Coco, were ranked below the trial mean for DEN and VAR in both trials. This contrasts with the Buren provenance of var. caribaea and the inland provenances of var. hondurensis, Mountain Pine Ridge, Potosi and Santa Clara, which were ranked above the trial mean for DEN and VAR in both trials. Provenance ranking was generally consistent for DEN VAR, VUB and DMI at the two sites.

The lack of significant provenance differences in DEN at Anasco-A could be due to site variability (0-35 percent slope) or to the fact that topsoil from Anasco-B was pushed on to Anasco-A during site preparation (Liegel et al., 1983). The difference in soil fertility might also explain differences in provenance ranking between the two trials as well as the fact that the trial mean for DEN was 7 percent greater at Anasco-A. The improved fertility of Anasco-A would partly explain why this trial produced 56 percent more volume under bark than the Anasco-B trial. The greater volume and density production at Anasco-A indicate that rapid tree growth does not necessarily result in wood of lower density. The common environment of two trees per plot at Anasco-A could have also influenced provenance differences in DEN since the Anasco-B trial is represented by one tree per plot.



Source	df	MS and p value			
Blocks	4	0.0018	0.0014	15040	3933
Provenances	15	0.0069 (p=0.345)	0.0048 (p<0.001)	16520 (p=0.005)	3067 (p=0.018)
s. e. provenance	27		14	25	12

FIGURE 2.1 Analysis of variance and ranked means for densitometric density (DEN), within sample density variation (VAR), volume under bark (VUB) and dry matter index (DMI) of *P. caribaea* provenances at Anasco-A.



Source	df	MS and p value			
Blocks	4	0.0066	0.0019	25958	5529
Provenances	14	0.0193 (p=0.021)	0.0165 (p<0.001)	8105 (p=0.026)	1842 (p=0.022)
s. e. provenance	21		14	14	7

FIGURE 2.2 Analysis of variance and ranked means for densitometric density (DEN), within density sample variation (VAR), volume under bark (VUB) and dry matter index (DMI) of *P. caribaea* provenances at Anasco (B).

Despite the greater trial mean of DEN at the more fertile Anasco-A trial the values of VAR at Anasco-A and Anasco-B were almost equal at 114 kg m^{-3} and 115 kg m^{-3} , respectively. In a fertilizer trial superimposed on a progeny test of P. caribaea in Queensland, Kanowski (1986) found that fertilizer did not have a significant effect on VAR though DEN was significantly lower in plots receiving heavier fertilization. The lack of response to variation in soil fertility by VAR suggests that other factors such as rainfall, temperature, soil moisture stress, photoperiod and genotype are of greater importance in controlling this trait.

Provenances were significantly different ($p < 0.04$) for VUB and DMI in both trials. The Palacios provenance of var. caribaea was ranked last for both traits in both trials. The var. hondurensis provenances, Byfield, Mountain Pine Ridge and Santa Clara, were ranked above the trial means for VUB and DMI in both trials.

Chati, Zambia

The trial at Chati is at a higher elevation than any other trial evaluated in this thesis. Included in the trial are nine provenances of var. hondurensis, one provenance of var. bahamensis and one provenance of var. caribaea. There were two inclusions of the Poptun provenance of var. hondurensis allowing for the comparison of different collections from the same provenance. This trial has been previously reported on by Mikkola (1979), Gibson (1982), Gibson *et al.* (1983) and Wright *et al.* (1986a).

The results of the ANOVA are summarized in Figure 2.3 and the partial ANOVA table is contained in Table 2.2. Provenances were significantly different for DEN ($p < 0.05$) but not for VAR ($p > 0.25$). The Q statistic exceeded the range for DEN and VAR and has not been presented. The Andros provenance of var. bahamensis was ranked near the bottom for DEN while the var. caribaea provenance, Buren, was ranked slightly above the trial mean for

DEN. The two collections from Poptun were very different for DEN but not for VAR. This indicates the need for clear definitions of provenance in terms of specific area as well as numbers and identities of trees sampled. Although the statistical significance of provenance differences for VAR were low it is interesting that the var. hondurensis provenances, Santa Clara and Guanaja, had the highest and lowest values, respectively, while their values for DEN were almost identical.

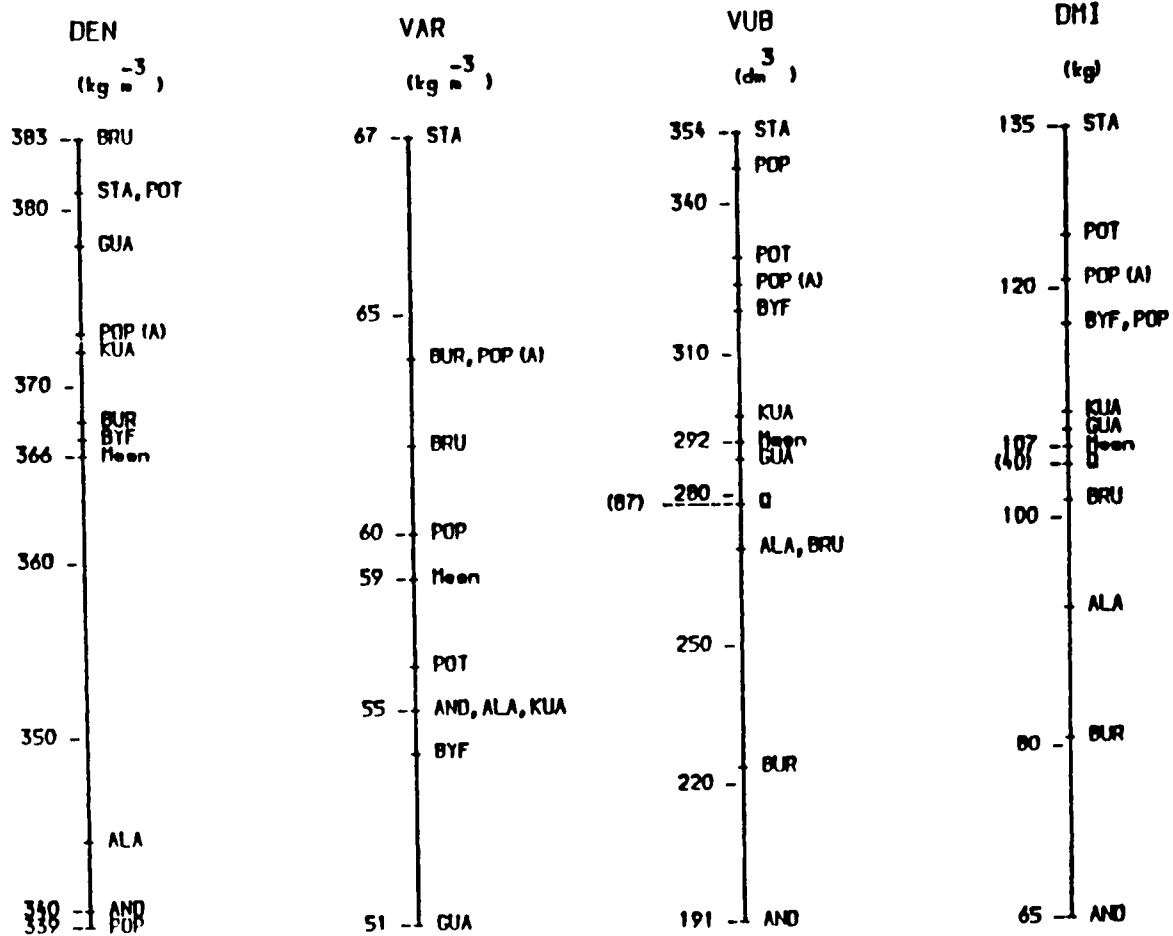
The overall trial means for DEN and VAR at Chati were among the lowest of the 14 trials assessed. This is perhaps due to the high altitude (1300m) since Barnes et al. (1977) have observed provenances of P. caribaea to show a decrease in density as site altitude increases.

Provenances were significantly different ($p < 0.001$) for VUB and DMI at Chati. The inland provenances of var. hondurensis, Byfield, Potosi, Santa Clara and both collections of Poptun, were ranked above the trial mean for VUB and DMI. The Andros provenance of var. bahamensis was ranked near the bottom for DEN and had the lowest VUB indicating that slow growth does not result in wood of greater density.

Loudima, Congo

The Loudima trial receives less rainfall than any other trial. There are nine provenances of var. hondurensis, one provenance each of var. bahamensis and var. caribaea. This trial has been reported on by Chaperon (1978), Gibson (1982) and Gibson et al. (1983).

The results of the ANOVA are summarized in Figure 2.4 and the partial ANOVA table is contained in Table 2.2. Provenances were significantly different for DEN ($p = 0.007$) and VAR ($p < 0.001$). The Andros provenance of var. bahamensis and the Palacios provenance of var. caribaea were significantly higher for DEN and VAR than



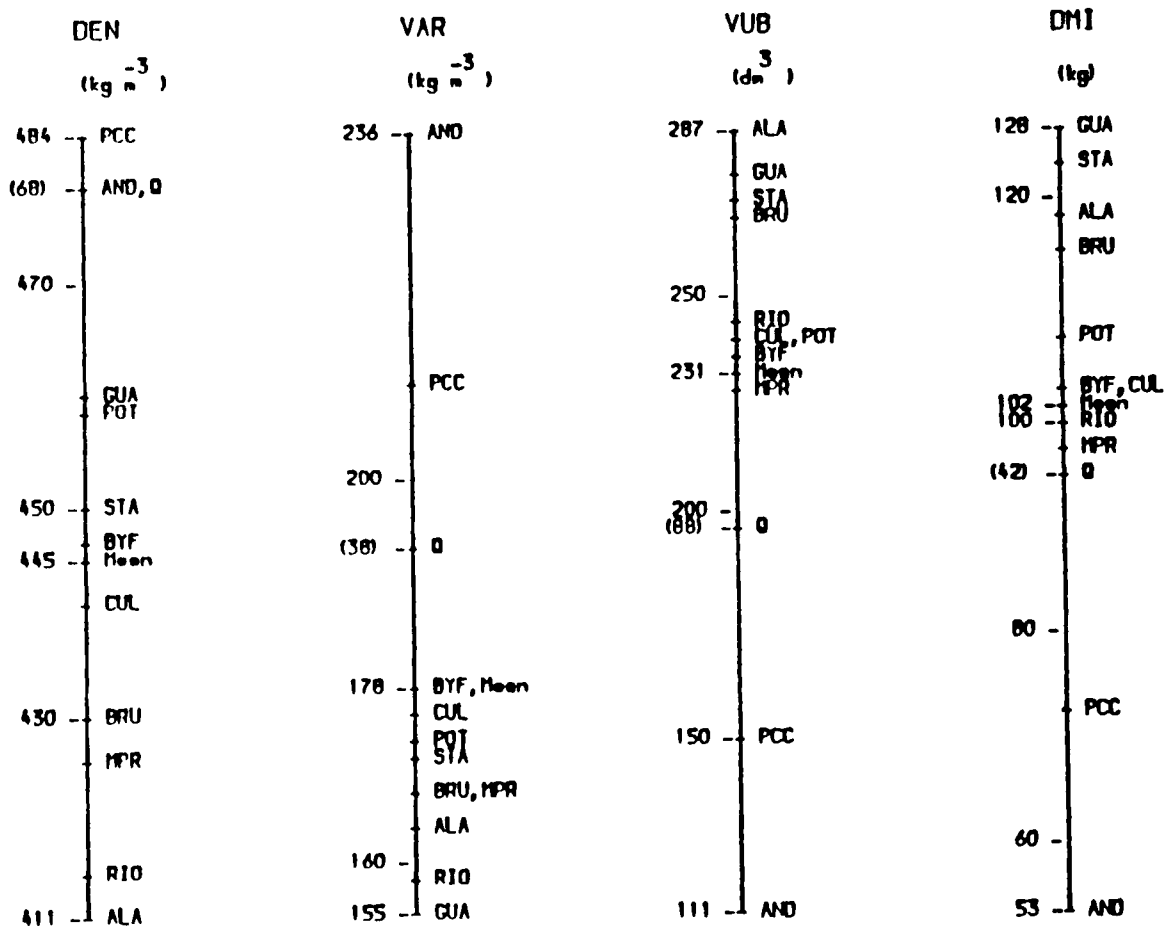
Source	df	MS and p value
Blocks	3	0.0092
Provenances	10	0.0068 (p<0.05)
e. e. provenance	11	

Source	df	MS and p value
Blocks	3	0.0008
Provenances	10	0.0005 (p>0.25)
e. e. provenance	5	

Source	df	MS and p value
Blocks	3	1555
Provenances	10	9986 (p<0.001)
e. e. provenance	11	

Source	df	MS and p value
Blocks	3	32105
Provenances	10	62926 (p<0.001)
e. e. provenance	8	

FIGURE 2.3 Analysis of variance, ranked means and the critical difference, Q, at the 5% level for densitometric density (DEN), within sample density variation (VAR), volume under bark (VUB) and dry matter index (DMI) of *P. caribaea* provenances at Chati.



Source	df	MS and p value
Blocks	4	0.0127
Provenances	10	0.0177 (p=0.007)
e. e. provenance	14	

Source	df	MS and p value
Blocks	4	0.0018
Provenances	10	0.0169 (p<0.001)
e. e. provenance	8	

Source	df	MS and p value
Blocks	3	2283
Provenances	10	87949 (p<0.001)
e. e. provenance	14	

Source	df	MS and p value
Blocks	3	296
Provenances	10	15039 (p<0.001)
e. e. provenance	8	

FIGURE 2.4 Analysis of variance, ranked means and the critical difference, Q, at the 5% level for densitometric density (DEN), within sample density variation (VAR), volume under bark (VUB) and dry matter index (DMI) of *P. caribaea* provenances at Loudima.

provenances of var. hondurensis as indicated by the Q statistic. The var. hondurensis coastal provenances, Alamicamba and Rio Coco, were ranked near the bottom for DEN and VAR. This contrasts with the var. hondurensis provenance, Guanaja, which was ranked above the trial mean for DEN and last for VAR. The low VAR and high DEN of Guanaja have also been observed at Chati, Zambia (Wright et al., 1986a). The Loudima trial had one of the highest overall means for VAR of the trials assessed in spite of the fact that for DEN the trial mean was ranked near the bottom. The high VAR could be the result of the severe dry season at the Loudima site which could result in a higher proportion of latewood and hence more variation in DEN from pith to bark.

Provenances were significantly different ($p < 0.001$) for VUB and DMI at Loudima. The provenances of var. hondurensis were significantly different and superior for VUB and DMI to the Palacios provenance of var. caribaea and to the Andros provenance of var. bahamensis.

San Pedro, Ivory Coast

The San Pedro trial has the highest mean annual temperature (26°C) of any of the trials sampled. Included at San Pedro were 15 provenances of var. hondurensis and two of var. caribaea. This trial has been reported on by Diabate (1978), Gibson (1982) and Gibson et al. (1983).

The results of the ANOVA are summarized in Figure 2.5 and the partial ANOVA table is contained in Table 2.2. Provenances were significantly different for VAR ($p = 0.01$) but not for DEN ($p = 0.32$). The Q statistic exceeded the range of DEN and has been omitted for this trait.

The var. caribaea provenances, Buren and Marbajita, were ranked above the trial mean for DEN and VAR as were the Byfield and Santa Clara provenances of var. hondurensis. This contrasts with

the var. hondurensis provenances, Alamicamba, Briones and Kuakil, which were ranked below the trial mean for DEN and VAR. The low DEN and VAR of Alamicamba was also observed at the Loudima, Congo trial.

The San Pedro trial had the highest overall mean for DEN of the 14 trials assessed. One possible reason for this is that this is the oldest trial assessed and wood density of pines is known to increase with increasing age. The high wood density of this trial could also be due to adequate monthly (>50mm) rainfall (Diabate, 1978) which allows for the continuous production of wood with latewood being formed during periods of reduced rainfall.

Provenances were significantly different ($p < 0.001$) at San Pedro for VUB and DMI. The Buren and Marbajita provenances of var. caribaea were inferior to provenances of var. hondurensis for VUB and DMI.

Mariti, South Africa

The Mariti trial is located at the second highest elevation of the 14 trials. The trial includes 10 provenances of var. hondurensis, four provenances of var. caribaea as well as local collections of var. hondurensis and P. elliotii. This trial has been discussed by van Wyk (1978a), Gibson (1982) and Gibson et al. (1983).

The results of the ANOVA are summarized in Figure 2.6 and the partial ANOVA table is contained in Table 2.2. Provenances were significantly different for DEN ($p < 0.025$) and VAR ($p < 0.001$) but the Q statistic exceeded the range for DEN and has been omitted for this trait. The P. elliotii seed source had the highest values for DEN and VAR and for the latter was more than twice as large as the next highest provenance. The increment cores taken from P. elliotii show distinct and wide bands of latewood while in the varieties of P. caribaea it can be difficult to

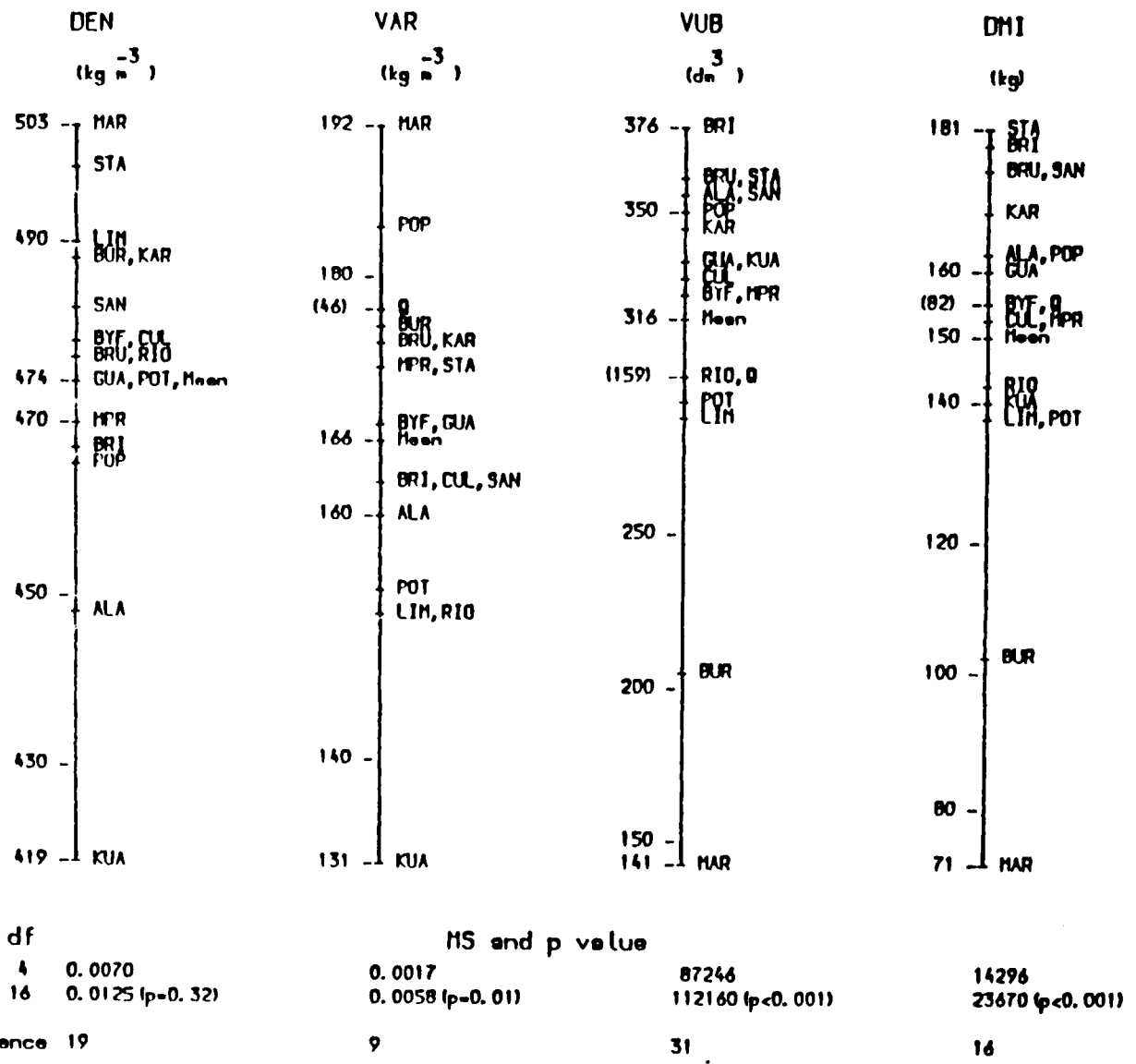


FIGURE 2.5 Analysis of variance, ranked means and the critical difference, Q, at the 5% level for densitometric density (DEN), within sample density variation (VAR), volume under bark (VUB) and dry matter index (DMI) of *P. caribaea* provenances at San Pedro.

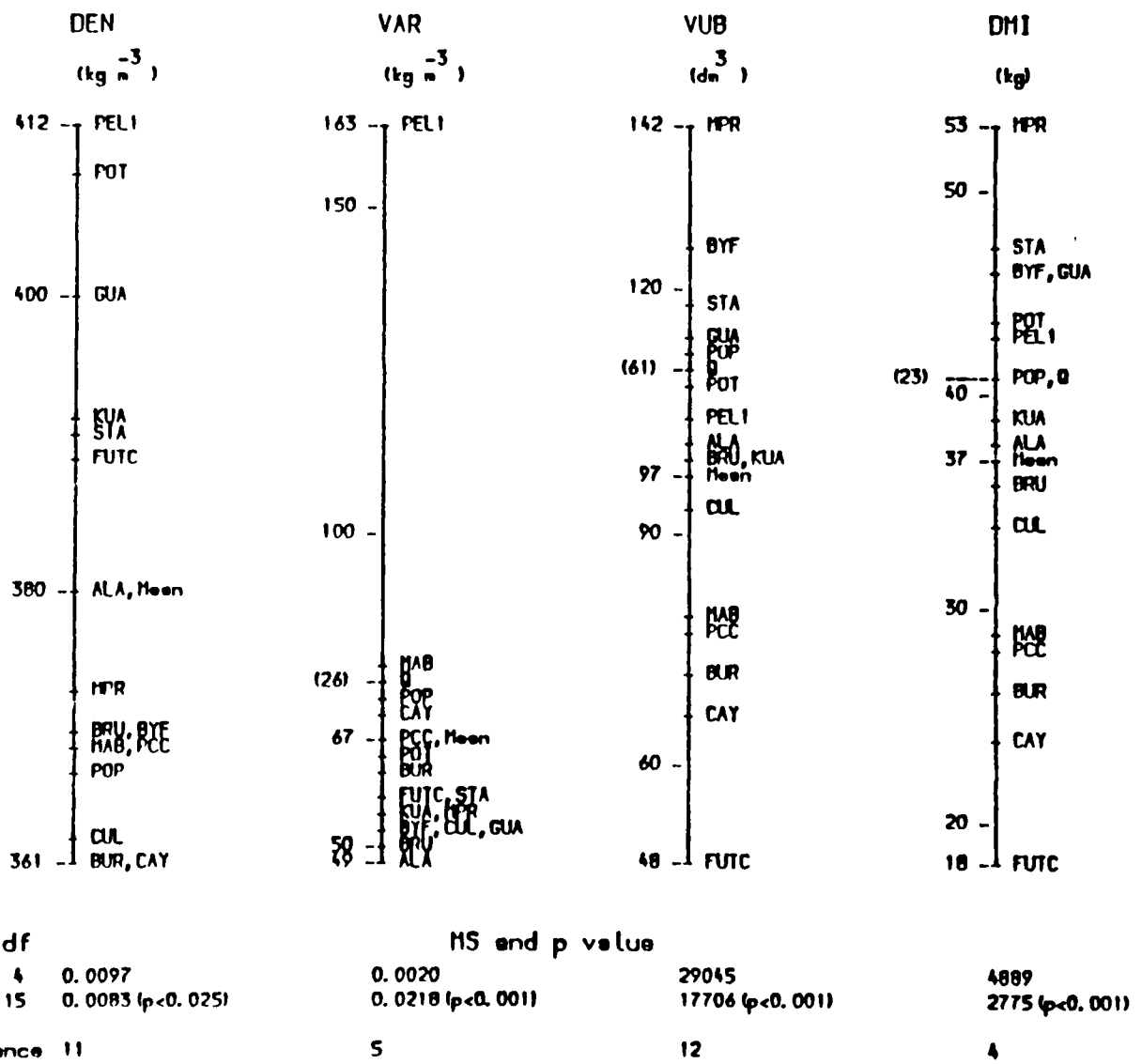


FIGURE 2.6 Analysis of variance, ranked means and the critical difference, Q, at the 5% level for densitometric density (DEN), within sample density variation (VAR), volume under bark (VUB) and dry matter index (DMI) of *P. caribaea* provenances at Mariti.

distinguish the annual ring and this may explain the high DEN and VAR of P. elliotii relative to P. caribaea. It is also likely that P. elliotii has an inherently higher wood density potential than does P. caribaea at this site. The greater wood uniformity of P. caribaea relative to P. elliotii observed by Lückhoff (1964) in South Africa would correspond to the low VAR of the former species found in this study.

The four provenances of var. caribaea, Buren, Caya la Mula, Marbajita and Palacios were ranked below the trial mean for DEN. The local seed source of var. hondurensis, Futululu, was ranked above the trial mean for DEN and VAR as was the the Guanaja provenance.

The Mariti trial was among the lowest for DEN and VAR of the 14 trials assessed. As with the Chati, Zambia trial, the high altitude of Mariti (1000m) could have influenced the low values of DEN and VAR since Barnes et al. (1977) have observed provenances of P. caribaea to decrease in gravimetric density with increasing elevation. The Mariti trial is subjected to dry winters and frost is possible. The combination of dry and cold weather could lead to decreased cambial activity which may result in the cessation of latewood formation which normally has greater density than earlywood.

There were significant differences ($p < 0.001$) between provenances for VUB and DMI at Mariti. The local source of var. hondurensis, Futululu, was ranked last for both VUB and DMI. The other provenances of var. hondurensis were superior for VUB and DMI to the provenances of var. caribaea.

KwaMbonambi, South Africa

The trial at KwaMbonambi consisted of eight provenances of var. hondurensis, seven provenances of var. caribaea and a local commercial control source of P. elliotii. There were two

collections in the trial of the var. hondurensis provenance Kuakil. This trial has been reported on by van Wyk (1978a), Gibson (1982) and Gibson et al. (1983).

The results of the ANOVA are summarized in Figure 2.7 and the partial ANOVA table is contained in Table 2.2. Provenances were significantly different ($p < 0.001$) for DEN and VAR. As at Mariti, the P. elliotii source had the highest DEN and VAR and this could also have been due to the distinct and wide bands of latewood in this species. The Alamicamba provenance of var. hondurensis was ranked near the bottom for DEN and VAR and this agrees with the results at San Pedro and Loudima. The insular provenance Guanaja, of var. hondurensis, was ranked above the trial mean for DEN and below the trial mean for VAR and this is similar to the results at Chati (Wright et al., 1986a) and Loudima. There was no significant difference in DEN and VAR between the two collections from the Kuakil provenance of var. hondurensis.

The provenances were significantly different ($p < 0.001$) for VUB and DMI at Kwambonambi. The two collections of Kuakil were not significantly different for these two traits. In spite of its high DEN, P. elliotii was ranked last for VUB and DMI. As at Mariti, the provenances of var. hondurensis were superior to those of var. caribaea for VUB and DMI.

Bukit Tapah, Malaysia

The Bukit Tapah trial receives more rainfall than any other trial assessed. Included in this trial are nine provenances of var. hondurensis, and one provenance each of var. bahamensis, var. caribaea and P. oocarpa. Gibson (1982) and Gibson et al. (1983) have reported on this trial.

The results of the ANOVA are summarized in Figure 2.8 and the partial ANOVA table is contained in Table 2.2. Provenances were

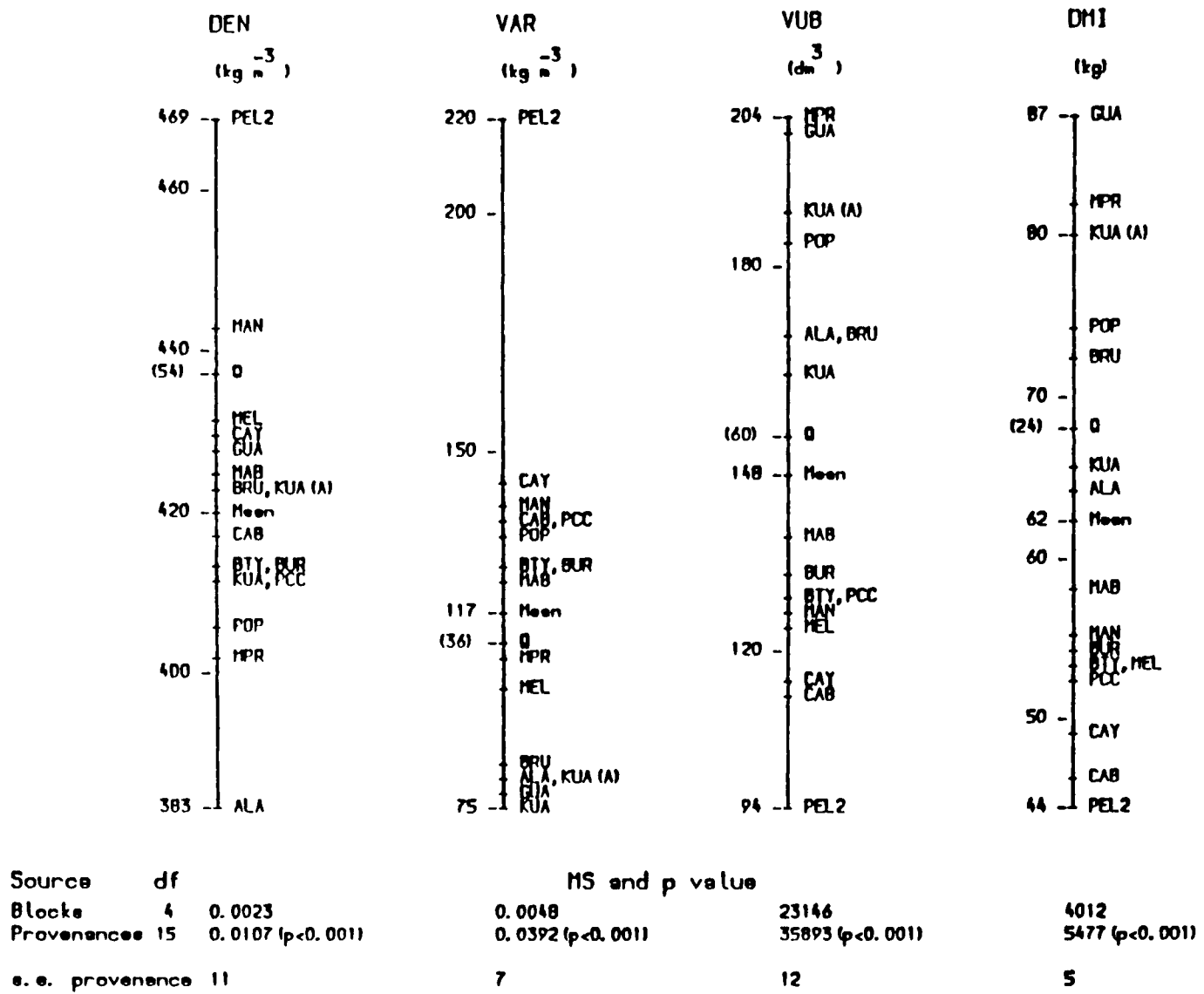


FIGURE 2.7 Analysis of variance, ranked means and the critical difference, Q , at the 5% level for densitometric density (DEN), within sample density variation (VAR), volume under bark (VUB) and dry matter index (DMI) of *P. caribaea* provenances at Kwambonambi.

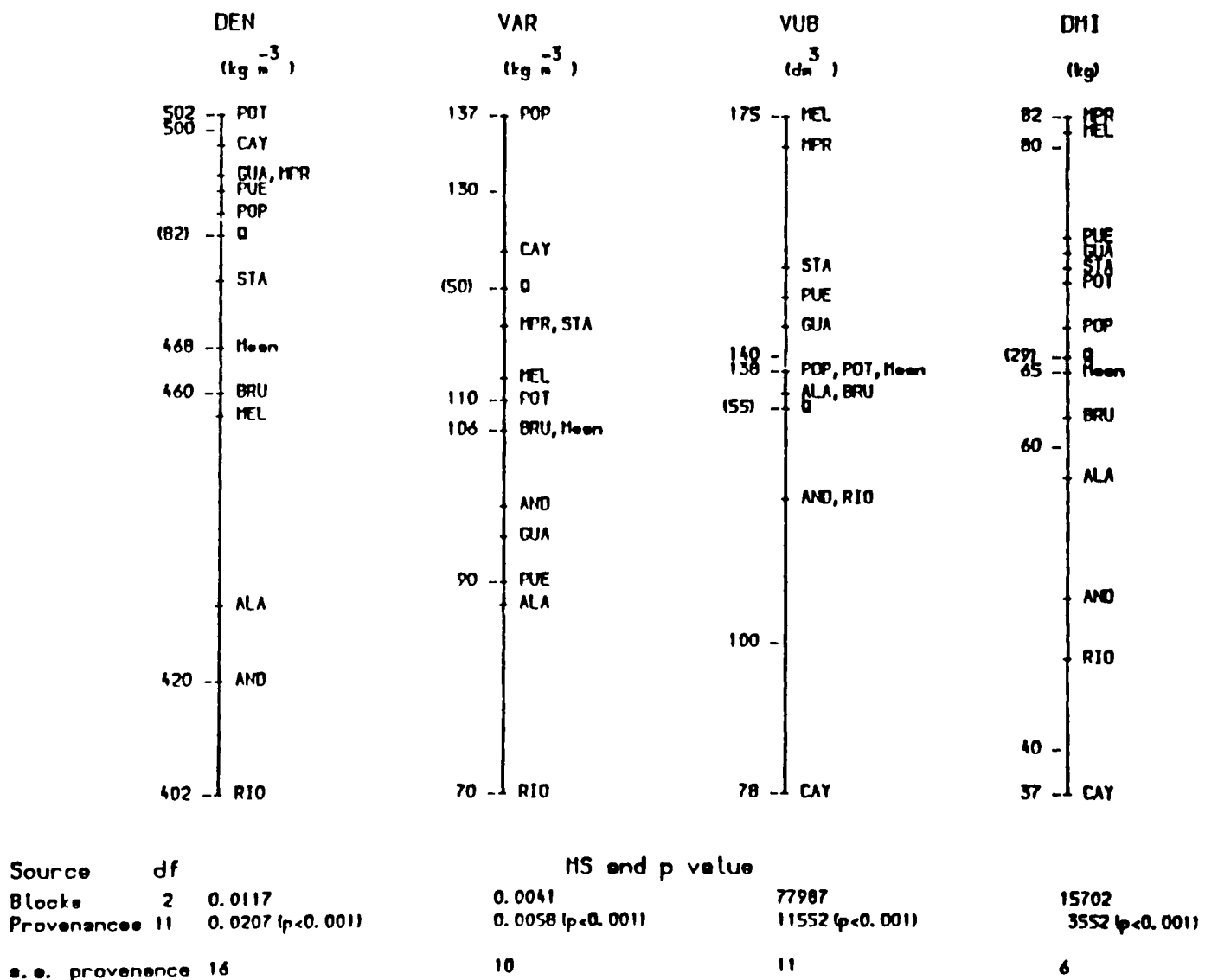


FIGURE 2.8 Analysis of variance, ranked means and the critical difference, Q , at the 5% level for densitometric density (DEN), within sample density variation (VAR), volume under bark (VUB) and dry matter index (DMI) of *P. caribaea* and *P. oocarpa* provenances at Bukit Tapah.

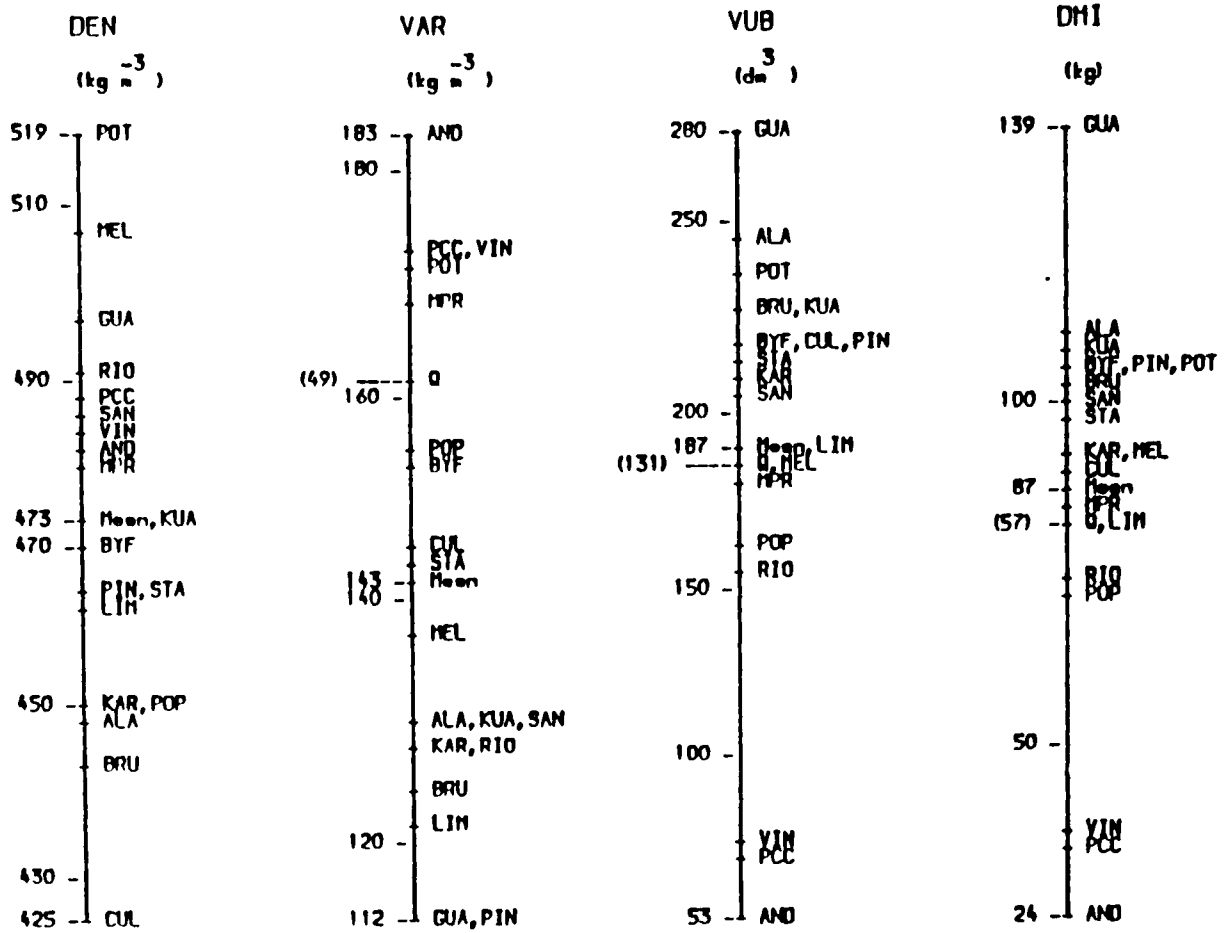
significantly different ($p < 0.001$) for DEN and VAR. The coastal provenances Alamicamba and Rio Coco of var. hondurensis were ranked near the bottom for DEN and VAR and this is similar to the Loudima trial. The Andros provenance of var. bahamensis was also ranked below the trial mean for DEN and VAR. The var. caribaea provenance, Caya la Mula, was ranked above the trial mean for DEN and VAR as were the inland provenances Mountain Pine Ridge, Poptun, Potosi and Santa Clara of var. hondurensis. The Pueblo Caido provenance of P. oocarpa was ranked near the top for DEN and near the bottom for VAR. The low VAR of P. oocarpa relative to P. caribaea confirms the findings of Wright *et al.* (1986a) in Zambia.

Provenances at Bukit Tapah were significantly different for VUB and DMI ($p < 0.001$). The Pueblo Caido provenance of P. oocarpa was ranked above the trial mean for both traits as were all of the inland provenances of var. hondurensis. The Caya la Mula provenance of var. caribaea was ranked last for VUB and DMI.

Drasa and Nanuku, Fiji

Identical trials were established at Drasa and Nanuku and include 16 provenances of var. hondurensis, one provenance of var. bahamensis and two provenances of var. caribaea. These trials have been discussed by Bell (1978). The results of the ANOVA are presented in Figure 2.9 for Drasa and in Figure 2.10 for Nanuku. The partial ANOVA table is contained in Table 2.2.

Provenances were significantly different for VAR ($p < 0.001$) but not for DEN ($p < 0.10$) at Drasa. The var. caribaea provenances, Palacios and Viñales, were ranked above the trial mean for DEN and VAR as was the Andros provenance of var. bahamensis and the inland provenances Mountain Pine Ridge and Potosi of var. hondurensis. The coastal provenances Alamicamba and Karawala of var. hondurensis were ranked below the trial mean for DEN and VAR. The Guanaja provenance of var. hondurensis was ranked above



Source	df	MS and p value
Blocks	9	0.0023
Provenances	18	0.0096 (p<0.001)
e. e. provenance	19	

FIGURE 2.9 Analysis of variance, ranked means and the critical difference, Q, at the 5% level for densitometric density (DEN), within sample density variation (VAR), volume under bark (VUB) and dry matter index (DMI) of *P. caribaea* provenances at Dreesa.

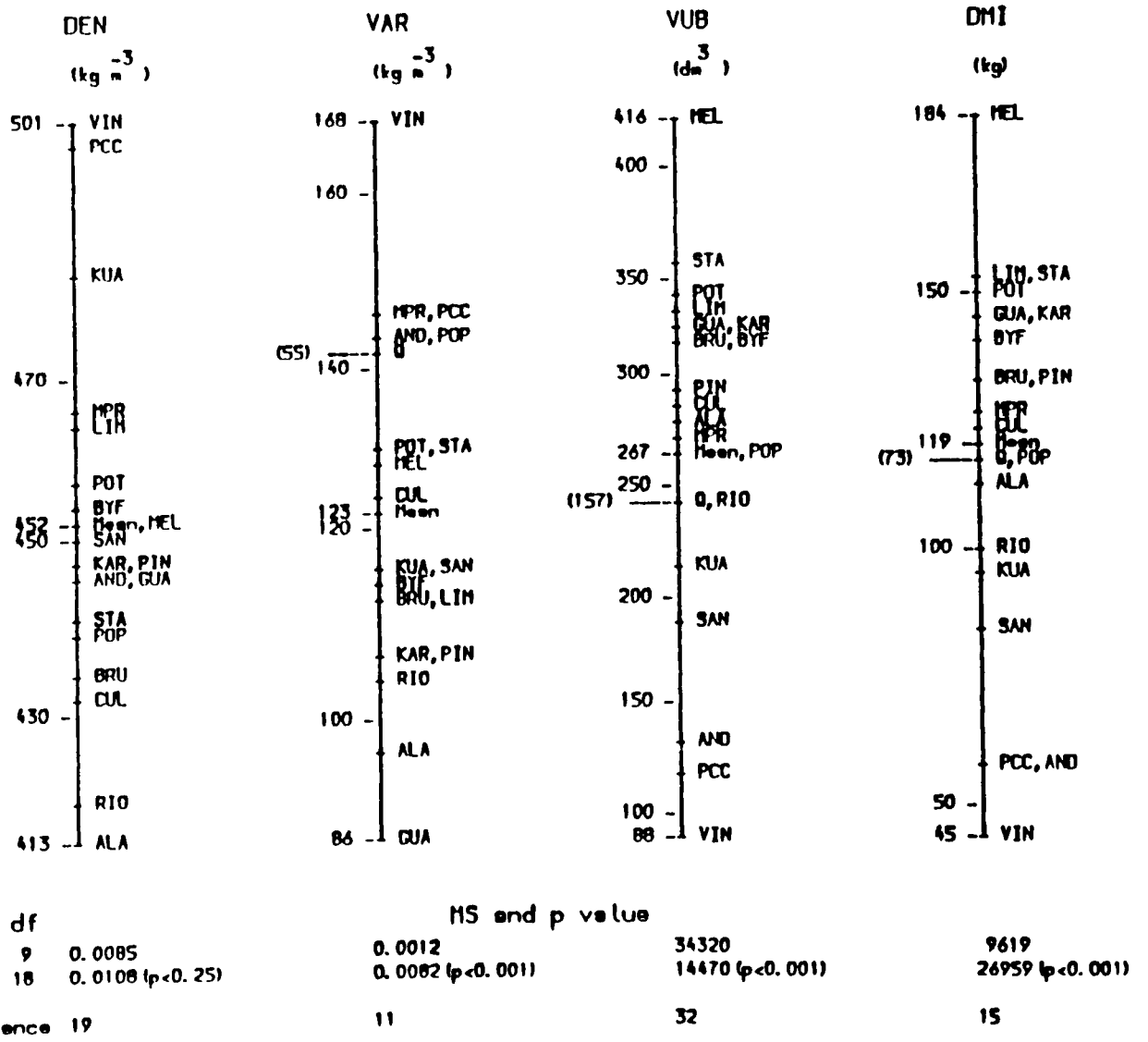


FIGURE 2.10 Analysis of variance, ranked means and the critical difference, Q, at the 5% level for densitometric density (DEN), within sample density variation (VAR), volume under bark (VUB) and dry matter index (DMI) of *P. caribaea* provenances at Nanuku.

the trial mean for DEN and below the trial mean for VAR. This is similar to the performance of Guanaja at Chati, Loudima and KwamBonambi.

At Nanuku, provenances were significantly different for VAR ($p, 0.001$) but not for DEN ($p < 0.25$). The var. caribaea provenances Palacios and Viñales were ranked above the trial mean as at Drasa. The inland provenances Mountain Pine Ridge and Potosi of var. hondurensis were also ranked above the trial mean for DEN and VAR at Nanuku as well as at Drasa. The coastal provenances Alamicamba, Karawala and Rio Coco of var. hondurensis were ranked below the trial mean for DEN and VAR at Nanuku.

The overall DEN and VAR at Drasa were larger than those at the higher altitude Nanuku site and confirm the results reported by Barnes *et al.* (1977) and the results at Chati and Mariti. Provenance mean values were significantly correlated between locations for VAR ($r = 0.782$) but no correlation was attempted for DEN due to the lack of statistically significant provenance differences for this trait at both Drasa and Nanuku.

There were significant differences ($p < 0.001$) between provenances for VUB and DMI at Drasa and Nanuku. The provenances Palacios and Viñales of var. caribaea and the Andros provenance of var. bahamensis were ranked at the bottom for VUB and DMI.

Beerburrum, Australia

The trial at Beerburrum consists of 11 provenances of var. hondurensis as well as two local sources of that variety. The local sources were selected for form and volume traits and not for wood density (Nikles and Spidy, 1973). This trial has been reported on by Nikles (1978), Gibson (1982) and Gibson *et al.* (1983).

The results of the ANOVA are summarized in Figure 2.11 and the

partial ANOVA is contained in Table 2.2. Provenances were significantly different for VAR ($p < 0.001$) but not for DEN ($p = 0.18$). The Q statistic exceeded the range for DEN and has been omitted. The insular provenance Guanaja was ranked above the trial mean for DEN and below it for VAR as at several of the trials. The inland provenances Poptun, Potosi and Santa Clara were ranked above the trial mean for DEN and VAR as was the local source, 13OR. The coastal provenances Alamicamba, Karawala and Rio Coco were ranked below the trial mean for DEN and VAR. There was no significant difference in DEN and VAR between the two local sources.

Provenances were significantly different ($p < 0.001$) for VUB and DMI at Beerburum. The two local collections were both ranked above the mean for VUB and DMI. The provenances Rio Coco and Santos were ranked near the bottom for DEN and VUB indicating that slow growth does result in wood of higher density.

Byfield, Australia

There were 16 provenances of var. hondurensis and two local sources of this variety at Byfield. This trial has been reported on by Nikles (1978), Gibson (1982) and Gibson et al. (1983).

The ANOVA results are summarized in Figure 2.12 and the partial ANOVA table is contained in Table 2.2. Provenances were significantly different for VAR ($p < 0.001$) but not for DEN ($p = 0.31$). The Q statistic has been omitted for DEN. The high F ratio for blocks is likely due to a fertilizer experiment being superimposed over the trial.

The inland provenances Limones, Potosi and Santa Clara were ranked above the trial mean for DEN and VAR while the coastal provenances Alamicamba, Karawala and Rio Coco were ranked below the trial mean for DEN and VAR. The insular source Guanaja was ranked near the top for DEN but was ranked near the bottom for

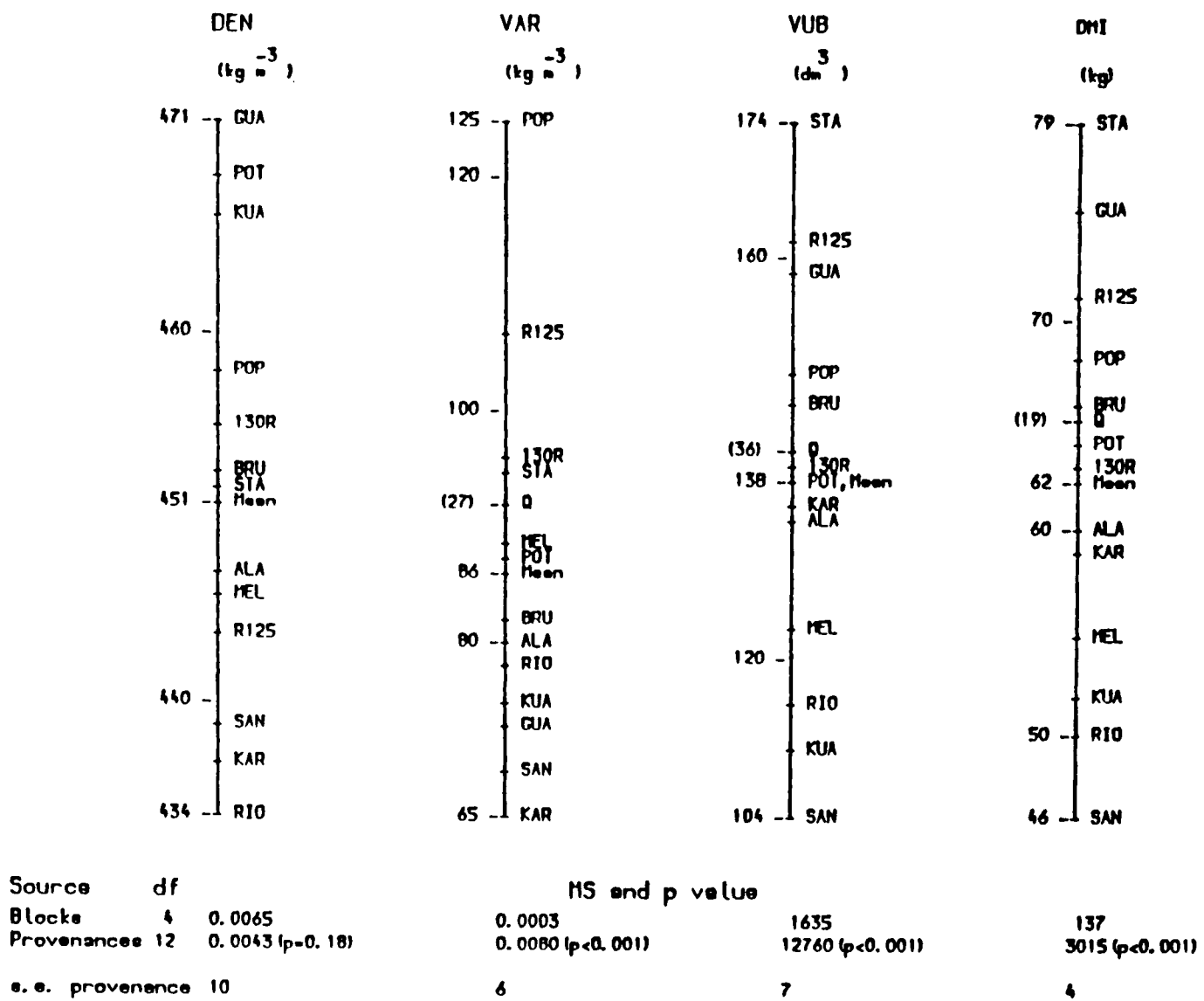


FIGURE 2.11 Analysis of variance, ranked means and the critical difference, Q , at the 5% level for densitometric density (DEN), within sample density variation (VAR), volume under bark (VUB) and dry matter index (DMI) of *P. caribaea* provenances at Beerburrum.

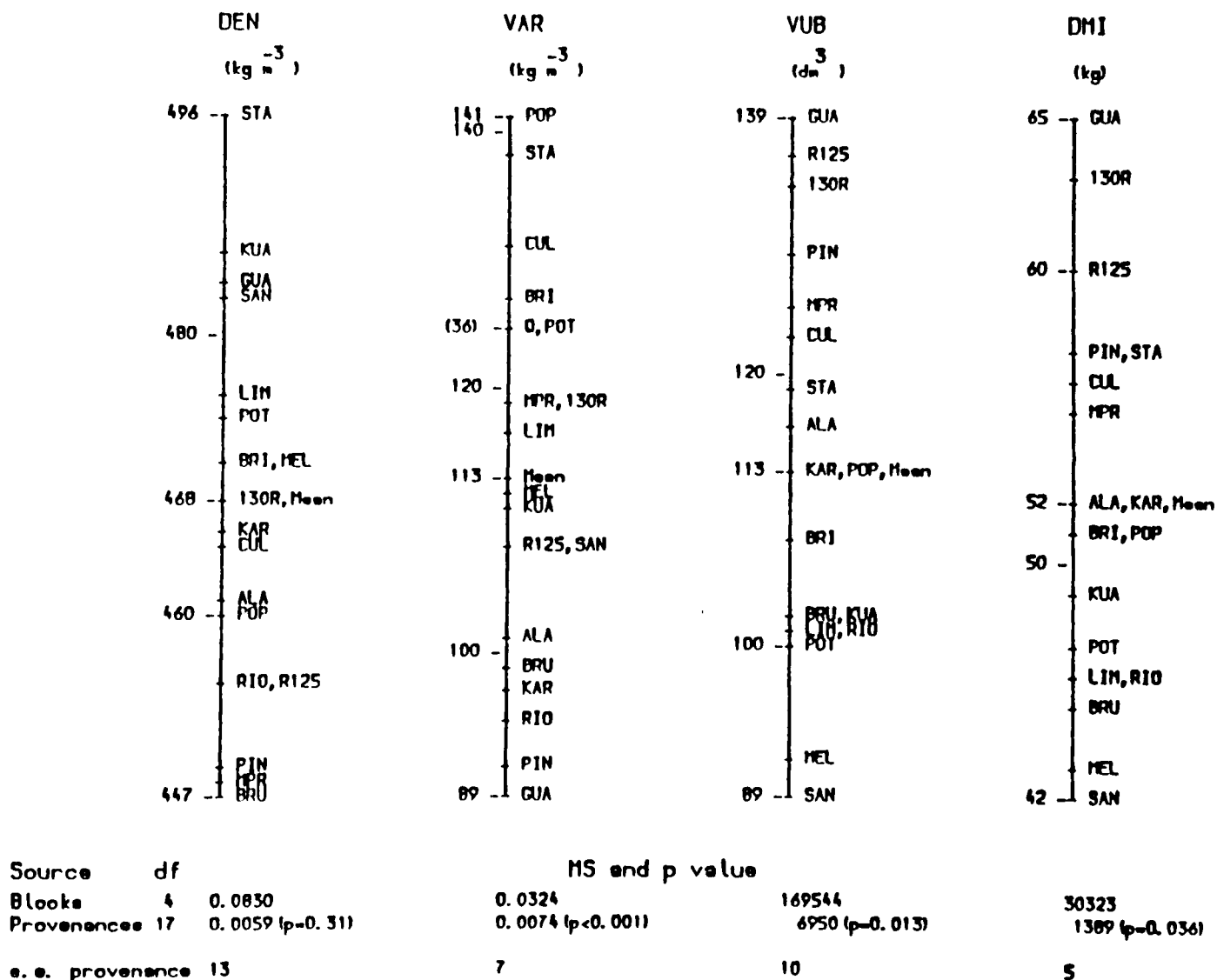


FIGURE 2.12 Analysis of variance, ranked means and the critical difference, Q , at the 5% level for densitometric density (DEN), within sample density variation (VAR), volume under bark (VUB) and dry matter index (DMI) of *P. caribaea* provenances at Byfield.

VAR. There was no significant difference between the local sources for DEN or VAR.

The provenances at Byfield were significantly different for VUB ($p=0.013$) and DMI ($p=0.036$). The two local collections were ranked near the top for VUB and DMI though the insular provenance Guanaja exceeded both of them for these traits. As at Beerburrum, the Santos provenance was ranked last for VUB and DMI.

Cardwell, Australia

The trial at Cardwell consists of 16 provenances of var. hondurensis and one provenance of var. caribaea. Previous work by Garcia de Leon (1982) included densitometric analysis of seven of the faster growing var. hondurensis provenances at Cardwell and these provenances have not been included in the current assessment. The performance of provenances at Cardwell has also been discussed by Gibson (1982) and Gibson et al. (1983).

The results of the ANOVA are summarized in Figure 2.13 and the partial ANOVA is contained in Table 2.2. Provenances were significantly different for VAR ($p<0.001$) but not for DEN ($p=0.68$). The Q statistic exceeded the range of DEN and has not been presented for this trait. The inland provenances of var. hondurensis were ranked higher for VAR than the coastal provenances. The Pinar provenance of var. caribaea was ranked the lowest for VAR but was ranked among the highest for DEN. The seven provenances of var. hondurensis evaluated by Garcia de Leon (1982) were ranked below the trial mean (456 kg m^{-3}) of the current assessment.

Provenances were significantly different for VUB ($p=0.023$) and DMI ($p=0.009$). The local source of var. hondurensis, Byfield, was significantly higher for VUB and DMI than the other provenances.

Jari, Brazil

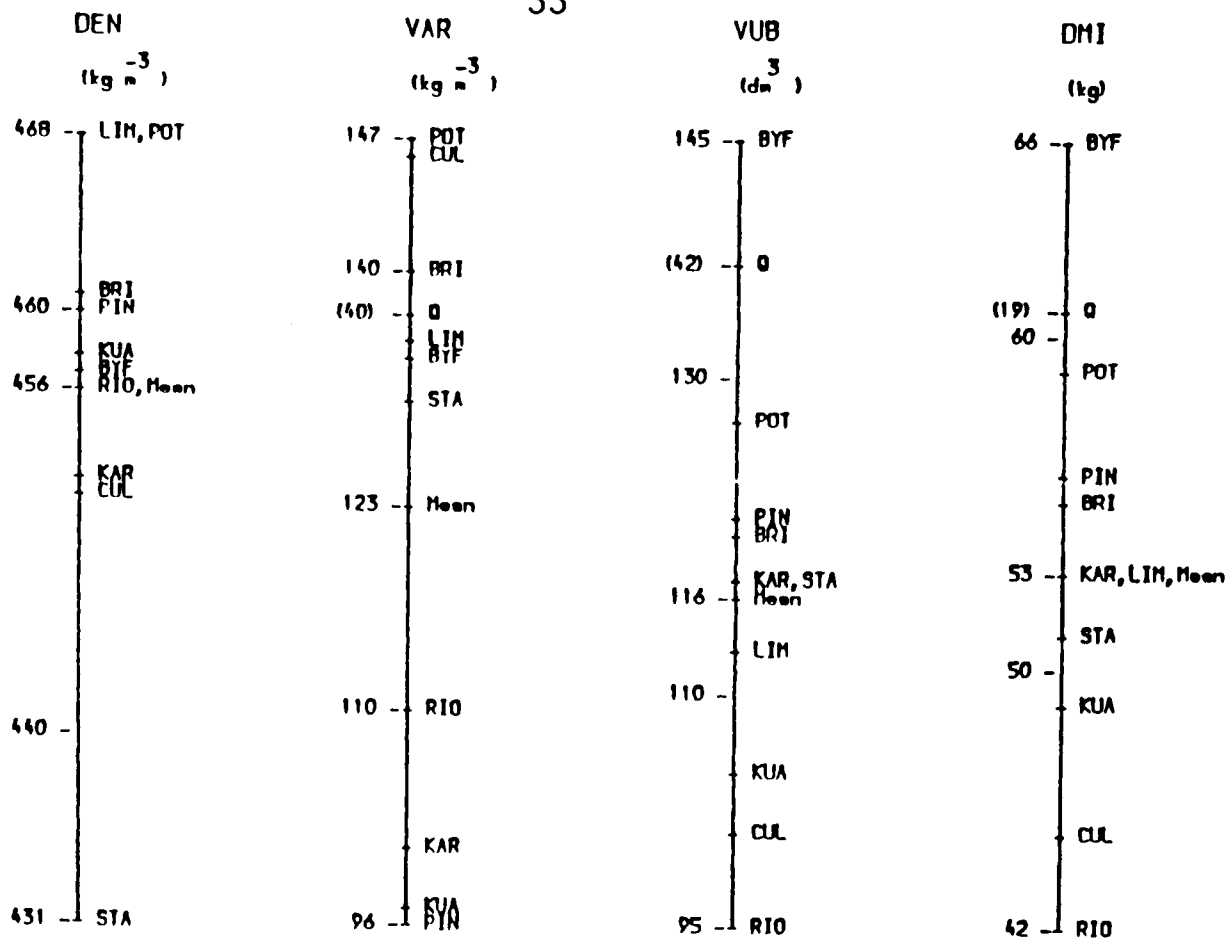
The trial at Jari contained 13 provenances of var. hondurensis, two provenances of var. caribaea and one provenance of var. bahamensis. Previous work by Garcia de Leon (1982) on wood samples from the Jari trial included seven of the faster growing provenances of var. hondurensis and these provenances have not been included in the current assessment. This trial has also been reported on by Gibson (1982), Woessner (1983) and Gibson et al (1983).

The results of the ANOVA are summarized in Figure 2.14 and the partial ANOVA can be found in Table 2.2. Provenances were significantly different for VAR ($p < 0.001$) but not for DEN ($p = 0.096$) and the Q statistic has been omitted for DEN. The var. caribaea provenances, Manuel and Palacios, were ranked at the top for DEN and VAR and for mean density this confirms the findings of Woessner (1983). The Andros provenance of var. bahamensis was ranked near the top for VAR and near the bottom for DEN. Woessner (1983) also observed that the Andros provenance was ranked the lowest for gravimetric density. The seven provenances of var. hondurensis evaluated by Garcia de Leon (1982) were ranked below the mean density of the lowest ranked provenance, Culmi, in the current assessment. The studies do show that provenance ranking does not differ between the different density determination methods and the different ages of assessment.

There were significant differences between provenances for VUB ($p < 0.001$) and DMI ($p = 0.008$). The provenances of var. bahamensis and var. caribaea were ranked at the bottom for VUB and DMI.

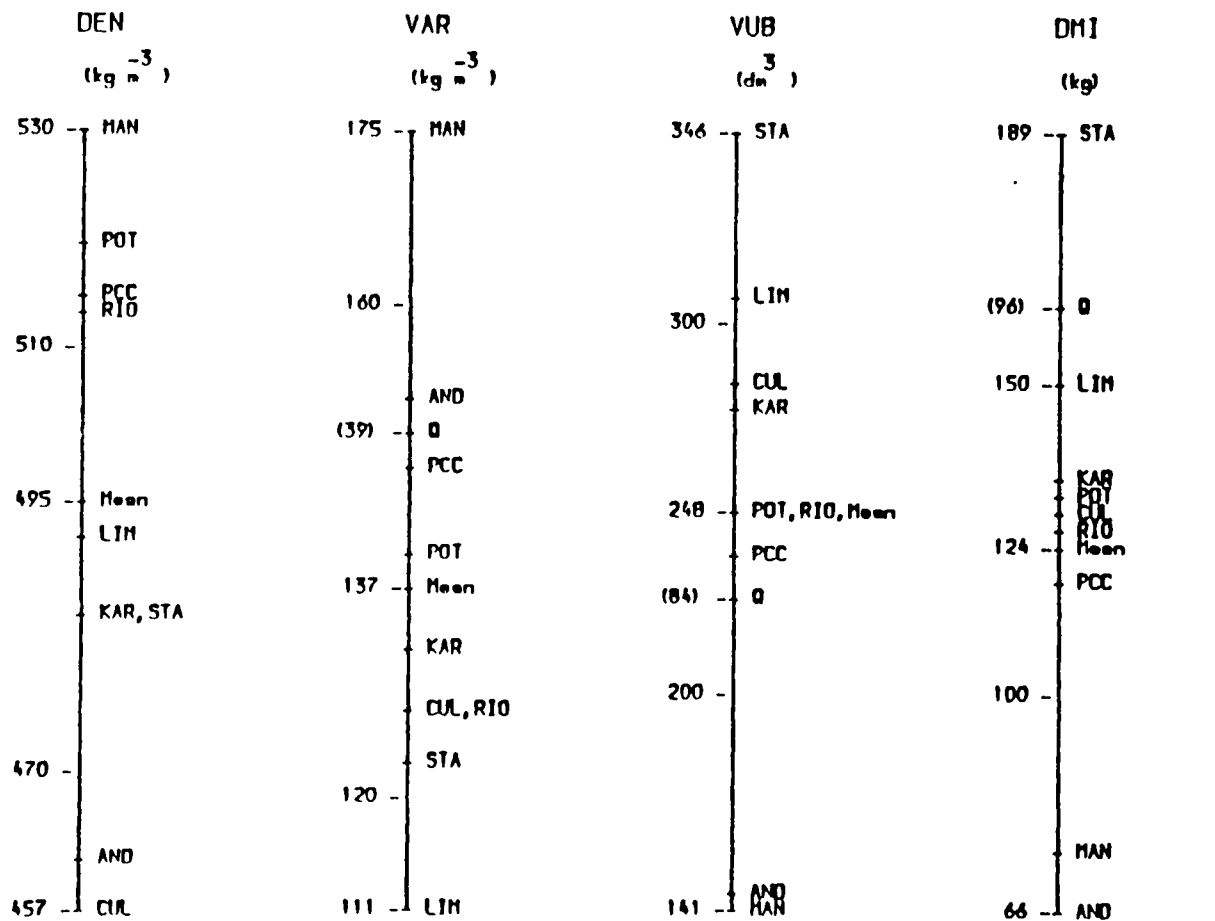
Conclusion

Provenances of P. caribaea were significantly different ($p < 0.05$) for VUB at the fourteen sites evaluated. For DEN, there were significant differences ($p < 0.05$) at only seven of the 14 sites.



Source	df	MS and p value			
Blocks	4	0.009	0.0021	4785	985
Provenances	9	0.0033 (p=0.68)	0.0123 (p<0.001)	5983 (p=0.023)	1391 (p=0.009)
s. e. provenance	12		8	9	4

FIGURE 2.13 Analysis of variance, ranked means and the critical difference, Q, at the 5% level for densitometric density (DEN), within sample density variation (VAR), volume under bark (VUB) and dry matter index (DMI) of *P. caribaea* provenances at Cardvell.



Source	df	MS and p value			
Blocks	4	0.0065	0.0003	28581	13055
Provenances	8	0.0202 (p=0.096)	0.0110 (p<0.001)	70619 (p<0.001)	40598 (p=0.008)
s. e. provenance	11		2	18	20

FIGURE 2.14 Analysis of variance, ranked means and the critical difference, Q, at the 5% level for densitometric density (DEN), within sample density variation (VAR), volume under bark (VUB) and dry matter index (DMI) of *P. caribaea* provenances at Jeri.

The large differences in DEN between trees within a provenance resulted in large standard errors for this trait. This in turn resulted in the lack of significant differences between provenances. The variability of DEN within a provenance, however, would allow the tree breeder to select trees with high or low density in the faster growing provenances.

The P. caribaea var. hondurensis provenances, Guanaja and Potosi, were often among the highest for DEN, though the former had low VAR at most of the sites in which it occurred. In terms of VUB and DMI, the superior provenances were Byfield, Guanaja and Santa Clara. The Andros provenance of P. caribaea var. bahamensis and the various provenances of P. caribaea var. caribaea were usually ranked near the bottom for VUB and DMI.

2.2 P. oocarpa and P. patula ssp. tecunumanii trials

Provenances of P. oocarpa and P. patula ssp. tecunumanii were assessed using the same design, model and expectation of mean squares as with P. caribaea (Table 2.1).

Anasco, Puerto Rico

The trial at Anasco receives more rainfall per annum (2090mm) than any other P. oocarpa trial. Included in the Anasco trial are 11 provenances of P. oocarpa, four provenances of P. patula ssp. tecunumanii and one provenance of P. caribaea. This trial has been reported on by Liegel et al. (1983) and by Liegel (1984a,b).

Table 2.2 Analysis of variance of plot totals for DEN and VAR of P. caribaea trials.

Site (observations per plot)	Source	df	MS(p value)	
			DEN	VAR
Anasco-A (4)	Blocks	4	0.0018	0.0014
	Provenances	15	0.0069 (p=0.345)	0.0048 (p<0.001)
	Residual	56	0.0070	0.0020
Anasco-B (2)	Blocks	4	0.0066	0.0019
	Provenances	14	0.0193 (p=0.021)	0.0165 (p<0.001)
	Residual	56	0.0089	0.0040
Chati (6)	Blocks	3	0.0092	0.0008
	Provenances	10	0.0068 (p<0.05)	0.0005 (p>0.25)
	Residual	30	0.0028	0.0006
Loudima (6)	Blocks	4	0.0127	0.0018
	Provenances	10	0.0177 (p=0.007)	0.0169 (p<0.001)
	Residual	40	0.0060	0.0018
San Pedro (6)	Blocks	4	0.0070	0.0017
	Provenances	16	0.0125 (p=0.32)	0.0058 (p=0.01)
	Residual	64	0.0107	0.0025
Mariti (6)	Blocks	4	0.0097	0.0020
	Provenances	15	0.0083 (p<0.025)	0.0218 (p<0.001)
	Residual	60	0.0040	0.0008
KwaMbonambi (6)	Blocks	4	0.0023	0.0048
	Provenances	15	0.0107 (p<0.001)	0.0392 (p<0.001)
	Residual	60	0.0034	0.0015
Bukit Tapah (6)	Blocks	2	0.0117	0.0041
	Provenances	11	0.0207 (p<0.001)	0.0058 (p<0.001)
	Residual	22	.0081	0.0067
Drasa (2)	Blocks	9	0.0078	0.0023
	Provenances	18	0.0108 (p<0.10)	0.0096 (p<0.001)
	Residual	162	0.0072	0.0019
Nanuku (2)	Blocks	9	0.0085	0.0012
	Provenances	18	0.0108 (p<0.25)	0.0082 (p<0.001)
	Residual	162	0.0075	0.0024
Beerburrum (6)	Blocks	4	0.0065	0.0003
	Provenances	12	0.0043 (p=0.18)	0.0080 (p<0.001)
	Residual	48	0.0029	0.0009
Byfield (6)	Blocks	4	0.0830	0.0324
	Provenances	17	0.0059 (p=0.31)	0.0074 (p<0.001)
	Residual	68	0.0051	0.0015
Cardwell (6)	Blocks	4	0.0009	0.0021
	Provenances	9	0.0033 (p=0.68)	0.0123 (p<0.001)
	Residual	36	0.0045	0.0021
Jari (6)	Blocks	4	0.0065	0.0003
	Provenances	8	0.0202 (p=0.096)	0.0110 (p<0.001)
	Residual	32	0.0107	0.0020

The results of the ANOVA are summarized in Figure 2.15 and the partial ANOVA table is in Table 2.3. There were no significant differences between provenances for DEN ($p=0.059$) or VAR ($p=0.137$) and the Q statistic has not been included for these traits. While not being statistically significant there do appear to be real differences between provenances. For example, the P. oocarpa provenances San Jose and Huehuetenango were ranked first and last, respectively, for both DEN and VAR. This is in contrast to the P. caribaea provenance Alamicamba which was ranked near the bottom for DEN but near the top for VAR.

The overall trial mean for DEN at Anasco was among the lowest of the trials evaluated. This could be due to the presence of adequate moisture during much of the growing season. This was also the youngest trial evaluated and one would expect density to be greater in the older trials.

Provenances were significantly different ($p<0.001$) for VUB and DMI. The four provenances of P. patula ssp. tecunumanii and the Alamicamba provenance of P. caribaea were significantly higher than P. oocarpa provenances for VUB and DMI as indicated by the Q statistic.

Conocoto, Ecuador

The trial of P. oocarpa at Conocoto has the highest elevation (2510m) of any trial evaluated. There were five provenances of P. oocarpa and three provenances of P. patula ssp. tecunumanii planted at Conocoto. The Jitotol provenance of P. oocarpa was not included in this analysis because the seed was collected from four trees (Greaves, 1979) and one or more of these trees appears to have been P. patula ssp. tecunumanii (Gibson, 1986). This trial has been reported on by Wright et al. (in press).

The results of the ANOVA are summarized in Figure 2.16 and the partial ANOVA table is in Table 2.3. There were no significant

differences between provenances for DEN ($p=0.34$) or VAR ($p=0.26$) and the Q statistic has not been presented for either trait. However, the three provenances of P. patula ssp. tecunumanii were ranked below the trial mean for DEN. The trees of the Jitotol provenance identified as P. oocarpa also had a DEN higher than that of the trees identified as P. patula ssp. tecunumanii. The overall trial mean of DEN at Conocoto was among the highest of the trials evaluated while the overall trial mean of VAR was among the lowest.

Provenances were not significantly different for VUB ($p=0.10$) or DMI ($p=0.18$) at Conocoto and the Q statistic has been omitted for these traits. The three provenances of P. patula ssp. tecunumanii were, however, ranked the highest for VUB and DMI in spite of the fact that their DEN was among the lowest in this trial.

Agudos, Brazil

The trial at Agudos contained 10 provenances of P. oocarpa and three provenances of P. patula ssp. tecunumanii. This trial has been reported on by Kageyama et al. (1977) and by Wright et al. (1986b).

The results of the ANOVA are reported in Figure 2.17 and the full ANOVA table is in Appendix 1. Provenances were significantly different for VAR ($p=0.01$) but not for DEN ($p=0.86$) and the Q statistic has not been included for DEN. The Lima provenance of P. oocarpa was ranked the highest for both DEN and VAR. The overall trial mean for DEN at Agudos was the highest of the trials evaluated and the value for VAR was among the highest.

There were significant differences between provenances at Agudos for VUB ($p<0.001$) and DMI ($p=0.002$). The provenances Camelias and Mountain Pine Ridge of P. patula ssp. tecunumanii were ranked at the top for VUB and DMI.

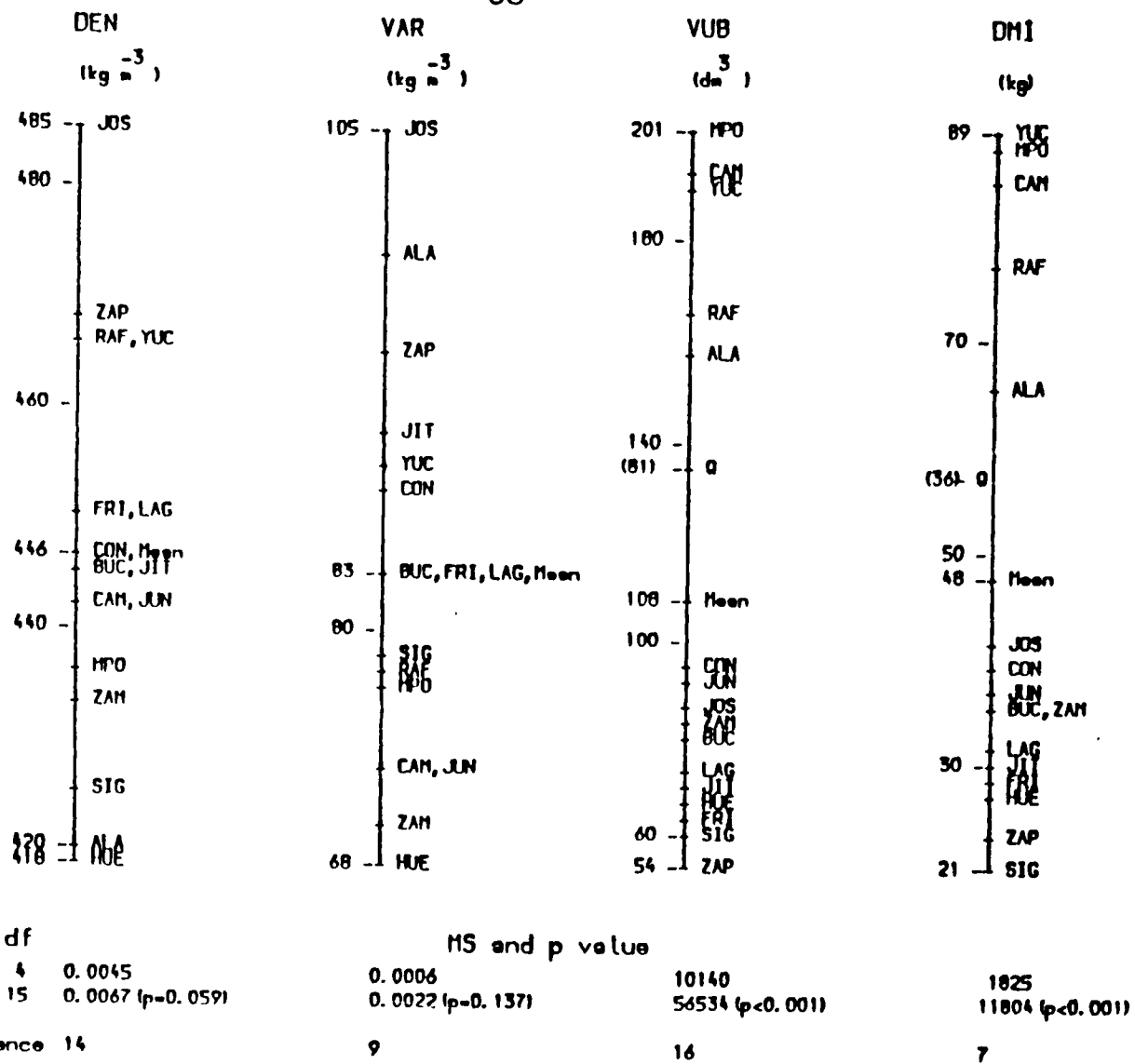


FIGURE 2.15 Analysis of variance, ranked means and the critical difference, Q, at the 5% level for densitometric density (DEN), within sample density variation (VAR), volume under bark (VUB) and dry matter index (DMI) of *P. oocarpa* and *P. patula* ssp. *tecunumanii* provenances at Anasco.

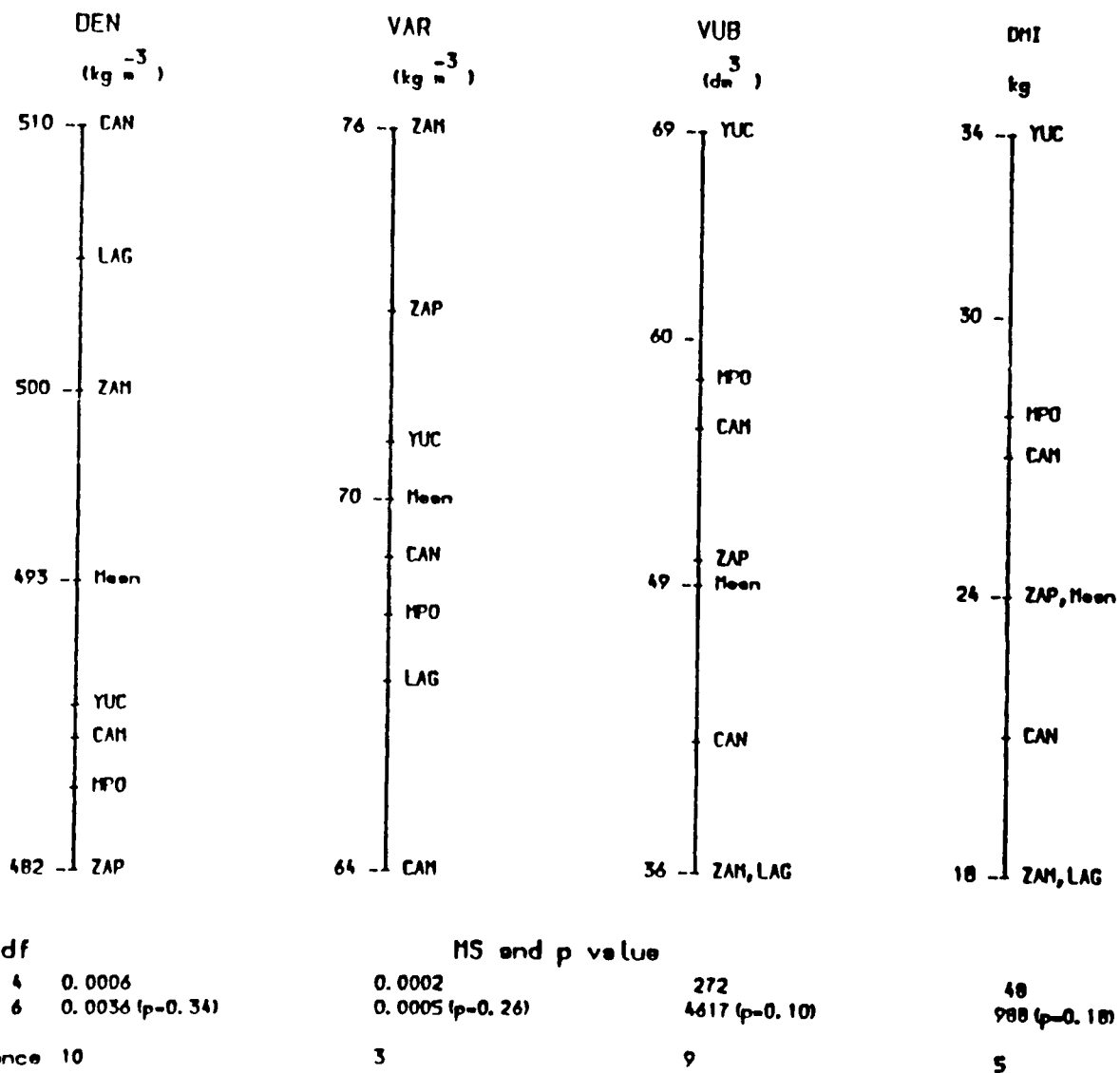


FIGURE 2.16 Analysis of variance, ranked means and the critical difference, Q, at the 5% level for densitometric density (DEN), within sample density variation (VAR), volume under bark (VUB) and dry matter index (DMI) of *P. oocarpa* and *P. patula* ssp. *tecunumanii* provenances at Conocoto.

Ndola East, Zambia

The Ndola East trial receives less rainfall than any of the P. oocarpa trials. Included at Ndola East are four provenances of P. patula ssp. tecunumanii and 14 provenances of P. oocarpa as well as a local collection of this species. The results of this trial have been previously reported on by Wright et al. (1986a).

The results of the ANOVA are contained in Figure 2.18 and the partial ANOVA table can be found in Table 2.3. Provenances were not significantly different ($p > 0.25$) for DEN or VAR. The Q statistic exceeded the range for DEN and VAR and has been omitted. One reason for the lack of statistical differences between provenances could be the fact that only two blocks were sampled, the other blocks having been destroyed by fire.

Provenances were not significantly different ($p > 0.25$) for VUB and DMI at Ndola East. However, the P. patula ssp. tecunumanii provenances were ranked above the trial mean for VUB and DMI. It is also interesting that the Huehuetenango provenance of P. oocarpa was ranked last for DEN and VUB indicating that slow growth does not necessarily result in wood of higher density.

Wilgeboom, South Africa

Included in the trial at Wilgeboom are four provenances of P. patula ssp. tecunumanii, 10 provenances of P. oocarpa, one provenance of P. caribaea and a local seed orchard collection of P. elliottii. This trial has been reported on by van Wyk (1978b).

The results of the ANOVA are summarized in Figure 2.19 and the partial ANOVA table is in Table 2.3. Provenances were significantly different ($p < 0.001$) for DEN and VAR. The P. caribaea provenance, Poptun, was ranked last for DEN and VAR. The P. elliottii seed source was also ranked near the bottom for DEN but was ranked the highest for VAR. The P. patula ssp.

tecunumanii provenances, Mountain Pine Ridge, Rafael and Yucul, were ranked above the trial mean for DEN and VAR while the provenance Camelias was ranked below the trial mean for these two traits.

The low DEN of Poptun at the relatively high altitude site (945m) was expected since Barnes et al. (1977) observed that provenances of P. caribaea have lower density at higher altitude. The high VAR of P. elliotii could be due to the distinct and wide bands of latewood observed in the increment cores of this species.

The provenances were significantly different ($p < 0.001$) for VUB and DMI at Wilgeboom. The provenances Camelias, Mountain Pine Ridge and Yucul of P. patula ssp. tecunumanii were significantly higher for VUB and DMI than the other provenances in this trial as indicated by the Q statistic. The P. elliotii source was ranked near the bottom for both DEN and VUB and its DMI production was only 52 percent of that obtained by Yucul.

KwaMbonambi, South Africa

The KwaMbonambi trial is at the lowest altitude (65m) of any of the P. oocarpa trials. Included at KwaMbonambi were four provenances and a local seed orchard collection of P. oocarpa, two provenances of P. patula ssp. tecunumanii and a commercial control of P. elliotii. This trial has been reported on by van Wyk (1978b).

The results of the ANOVA are summarized in Figure 2.20 and the partial ANOVA table is in Table 2.3. Provenances were significantly different for VAR ($p < 0.001$) but not for DEN ($p < 0.25$) and the Q statistic has not been presented for DEN. The P. elliotii source was ranked the highest for DEN and VAR and for the latter was 76 percent higher than the next highest provenance, Mountain Pine Ridge. The two provenances of P. patula ssp. tecunumanii, Camelias and Mountain Pine Ridge, were ranked

below the trial mean for DEN and their values for this trait were lower at Kwambonambi than at any other location.

There were significant differences ($p < 0.001$) between provenances for VUB and DMI at Kwambonambi. The Cañas provenance of P. oocarpa and the Camelias and Mountain Pine Ridge provenances of P. patula ssp. tecunumanii were clearly superior to the other provenances in terms of VUB and DMI. The P. elliottii source and the local source of P. oocarpa, Futululu, produced only 58 percent as much DMI as Canas.

Nzoia, Kenya

The P. oocarpa trial at Nzoia is the oldest trial that was evaluated. The trial was established with 11 provenances of P. oocarpa, four provenances of P. patula ssp. tecunumanii and one provenance of P. caribaea. This trial has been reported on by Chagala and Gibson (1984).

The results of the ANOVA are summarized in Figure 2.21 and the partial ANOVA table is in Table 2.3. Provenances were not significantly different for DEN ($p < 0.10$) or VAR ($p < 0.25$). However, the probability values for DEN and VAR, while not being statistically significant, do indicate real differences between provenances for these traits. The Alamicamba provenance of P. caribaea was ranked last for DEN and VAR. The Huehuetenango provenance of P. oocarpa was also ranked near the bottom for DEN and VAR. Provenances of P. patula ssp. tecunumanii were all ranked below the trial means for DEN and VAR with the exception of Camelias which was ranked near the top for DEN.

As at the low latitude site Conocoto, the overall trial mean for VAR at Nzoia was much lower than for the trials at higher latitude. The low VAR at Nzoia does not appear to be due to low DEN.

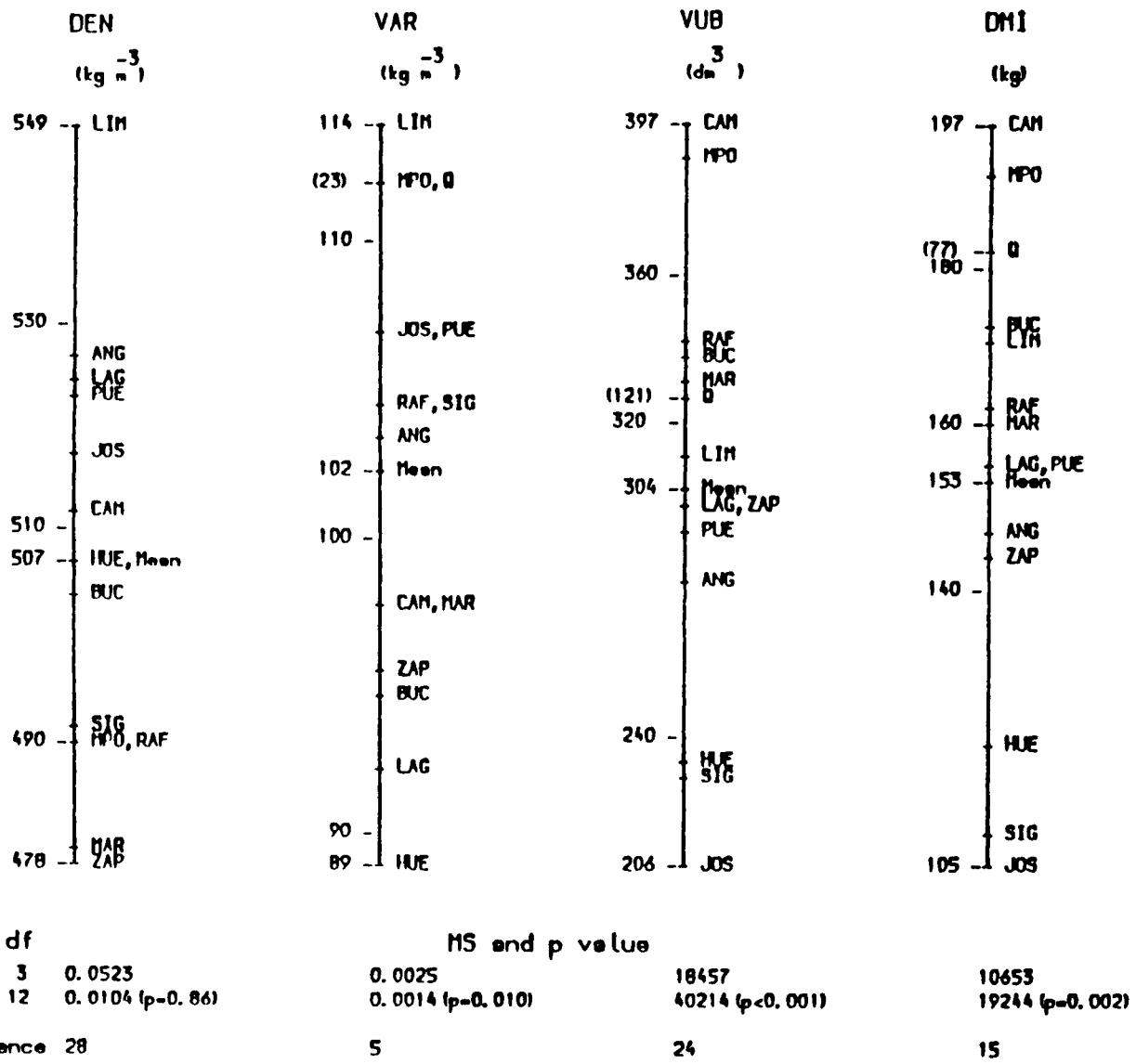


FIGURE 2.17 Analysis of variance, ranked means and the critical difference, Q, at the 5% level for densitometric density (DEN), within sample density variation (VAR), volume under bark (VUB) and dry matter index (DMI) of *P. oocarpa* and *P. patula* esp. *tecunumanii* provenances at Agudos.

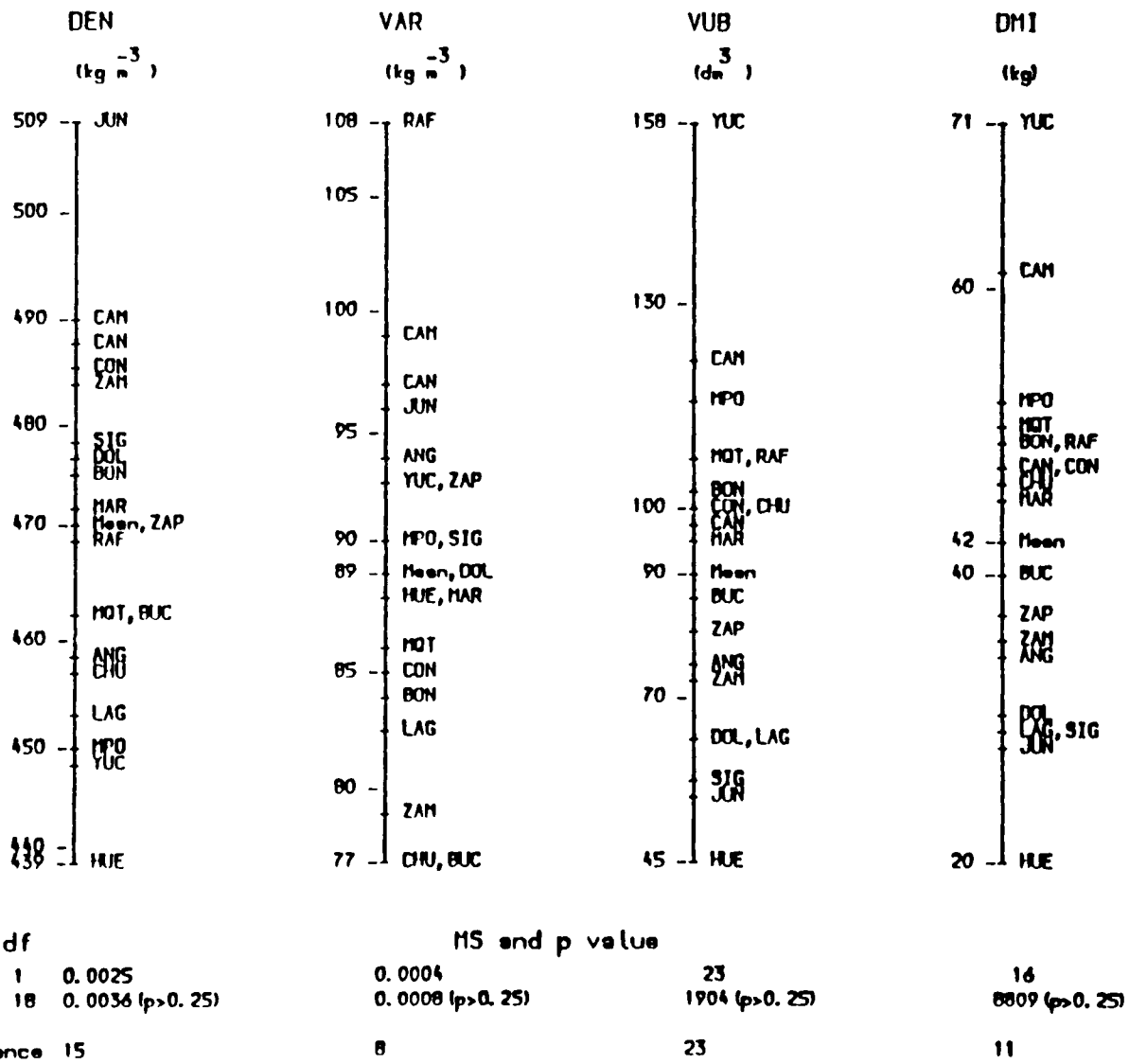


FIGURE 2.18 Analysis of variance, ranked means and the critical difference, Q, at the 5% level for densitometric density (DEN), within sample density variation (VAR), volume under bark (VUB) and dry matter index (DMI) of *P. oocarpa* and *P. patula* esp. *tecunumanii* provenances at Ndole East.

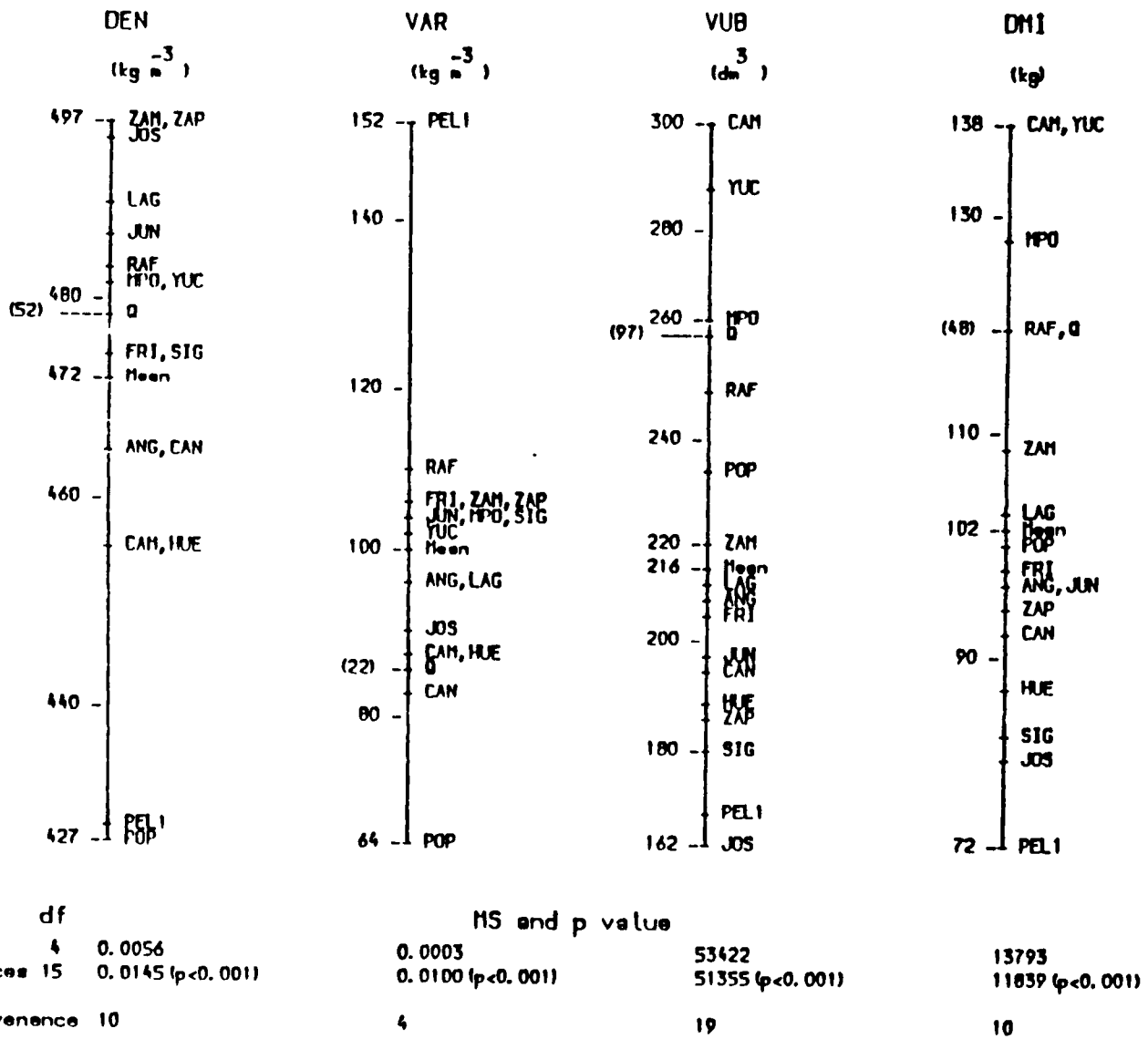


FIGURE 2.19 Analysis of variance, ranked means and the critical difference, Q, at the 5% level for densitometric density (DEN), within sample density variation (VAR), volume under bark (VUB) and dry matter index (DMI) of *P. oocarpa* and *P. patula* ssp. *tecunumanii* provenances at Wilgeboom.

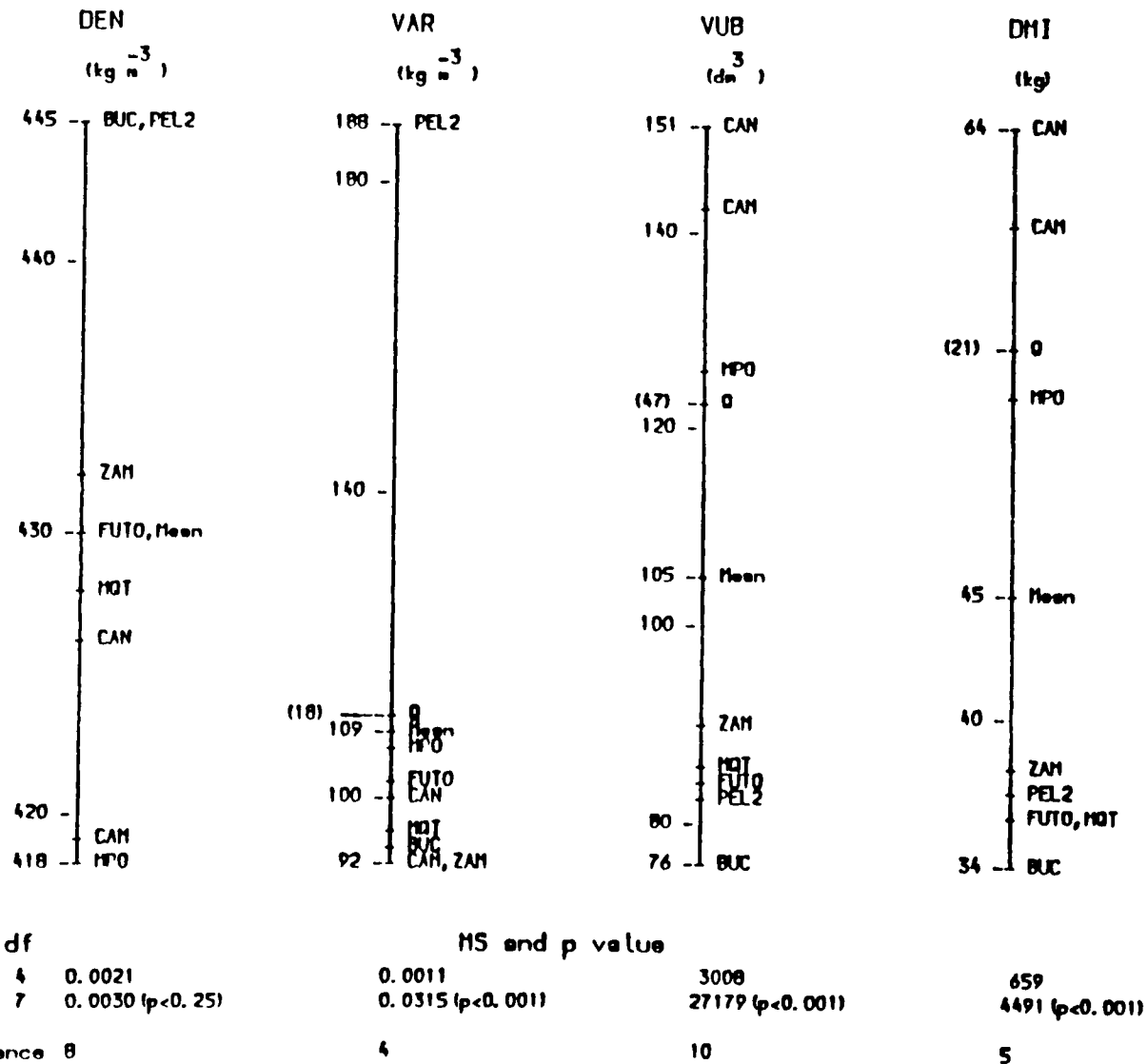


FIGURE 2.20 Analysis of variance, ranked means and the critical difference, Q, at the 5% level for densitometric density (DEN), within sample density variation (VAR), volume under bark (VUB) and dry matter index (DMI) of *P. oocarpa* and *P. patula* ssp. *tecunumanii* provenances at Kwambonambi.

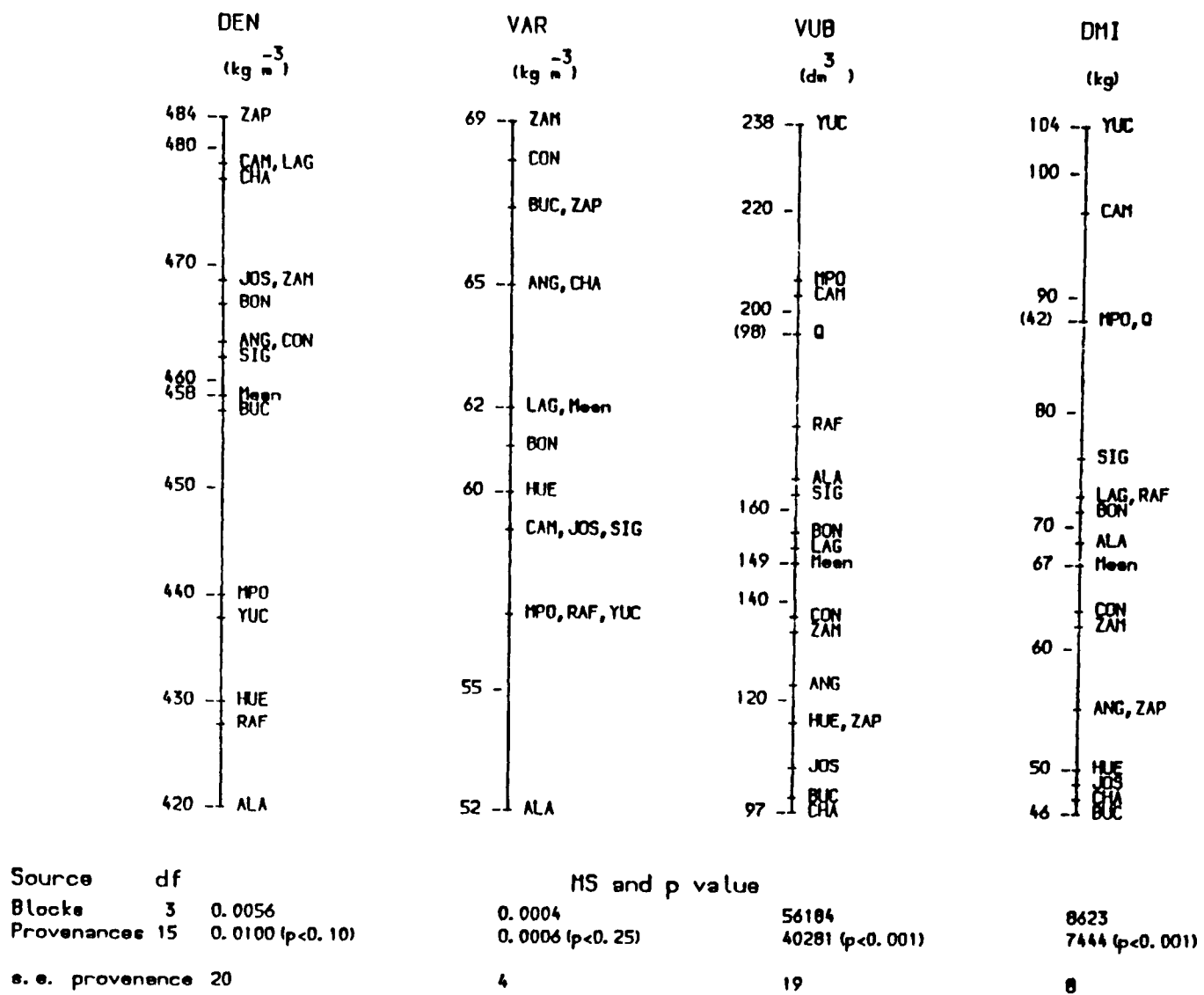


FIGURE 2.21 Analysis of variance, ranked means and the critical difference, Q, at the 5% level for densitometric density (DEN), within sample density variation (VAR), volume under bark (VUB) and dry matter index (DMI) of *P. oocarpa* and *P. patula* ssp. *tecunumanii* provenances at Nzola.

Provenances were significantly different ($p < 0.001$) for VUB and DMI at Nzoia. The P. patula ssp. tecunumanii provenances, Camelias, Mountain Pine Ridge and Yucul, were superior to the other provenances for VUB and DMI as indicated by the Q statistic.

Table 2.3 Analysis of variance of plot totals for DEN and VAR of P. oocarpa and P. patula ssp. tecunumanii trials.

Site (observations per plot)	Source	df	MS(p value)	
			DEN	VAR
Anasco (4)	Blocks	4	0.0045	0.0006
	Provenances	15	0.0067 (p=0.059)	0.0022 (p=0.137)
	Residual	60	0.0037	0.0014
Conocoto (6)	Blocks	4	0.0006	0.0002
	Provenances	6	0.0036 (p=0.34)	0.0005 (p=0.26)
	Residual	24	0.0030	0.0003
Agudos (6)	Blocks	3	0.0523	0.0025
	Provenances	12	0.0104 (p=0.86)	0.0014 (p=0.010)
	Residual	36	0.0186	0.0005
Ndola East (6)	Blocks	1	0.0025	0.0004
	Provenances	18	0.0036 (p>0.25)	0.0008 (p>0.25)
	Residual	18	0.0027	0.0008
Wilgeboom (6)	Blocks	4	0.0056	0.0003
	Provenances	15	0.0145 (p<0.001)	0.0100 (p<0.001)
	Residual	60	0.0031	0.0006
KwaMbonambi (6)	Blocks	4	0.0021	0.0011
	Provenances	7	0.0030 (p<0.25)	0.0315 (p<0.001)
	Residual	28	0.0019	0.0006
Nzoia (6)	Blocks	3	0.0056	0.0004
	Provenances	15	0.0100 (p<0.10)	0.0006 (p<0.25)
	Residual	45	0.0055	0.0004

Conclusion

Provenances of P. oocarpa and P. patula ssp. tecunumanii were significantly different for VUB at five of the seven sites. The provenances of P. patula ssp. tecunumanii were generally superior for VUB to provenances of P. oocarpa. For DEN, provenances were significantly different at only one site. As with provenances of P. caribaea, the lack of significant differences in DEN is likely due to large standard errors for this trait caused by large tree-

to-tree variation within a provenance. Opportunities thus exist to select trees with high or low DEN in the faster growing provenances.

The P. oocarpa provenances, Huehuetenango and Lagunilla, were ranked low and high for DEN, respectively. The former was also ranked near the bottom for VAR at most of the sites where it was planted. The P. patula ssp. tecunumanii provenances, Camelias, Mountain Pine Ridge, Rafael and Yucul, were clearly superior in terms of VUB and DMI.

2.3 Comparison of trials with similar environments

There were adjacent trials of P. caribaea, P. oocarpa and P. patula ssp. tecunumanii at only two sites though one other set of trials were similar enough in environmental conditions to be considered comparable. No statistical analysis of provenance means for DEN, VAR, VUB and DMI was felt to be justified since for one of the trial sets there were slight differences in the patterns of temperature and rainfall as well as trial ages. Details of experimental design and environmental conditions for the three sets of trials with similar environments are summarized in Tables 1.1 to 1.4. The comparisons between species made here should not be extrapolated to include other sites since the particular set of provenances and environmental conditions are only applicable to these three sites.

Anasco, Puerto Rico

The trials at Anasco were adjacent though one of the P. caribaea trials did have higher soil fertility (Liegel et al., 1983). The results of the ANOVA are presented in Figures 2.1 and 2.2 for the two trials of P. caribaea and in Figure 2.15 for the trial of P. oocarpa and P. patula ssp. tecunumanii at Anasco. The trials are compared together on Figure 2.22 and mean values from the two P. caribaea trials were used to represent this species. The

Alamicamba provenance of P. caribaea was included in both trials and was consistent in DEN, VAR, VUB and DMI. The ranking of provenances for DEN indicated that no single species had the highest value for this trait though the variation between provenances was large. The mean trial VAR was highest for provenances of P. caribaea. The provenances Alamicamba, Byfield and Santa Clara of P. caribaea and Camelias, Mountain Pine Ridge, Rafael and Yucul of P. patula ssp. tecunumanii had similar trial mean values for VUB though the latter did exceed the former in terms of DMI. These trials would thus suggest that the four provenances of P. patula ssp. tecunumanii would give greater yields of wood fiber over a rotation. Liegel (1984b), however, has observed that fast growing provenances of P. patula ssp. tecunumanii in Puerto Rico are highly susceptible to damage in cyclonic storms and this may favour the P. caribaea as the preferred species of the three tested here.

Mariti and Wilgeboom, South Africa

The results of the ANOVA are presented in Figure 2.6 for the P. caribaea trial at Mariti and in Figure 2.19 for the P. oocarpa and P. patula ssp. tecunumanii trial. Comparison of provenance means can be found in Figure 2.23. The trial mean values of DEN and VAR were lowest for P. caribaea. The provenances of P. patula ssp. tecunumanii were far superior in terms of VUB and DMI to provenances of P. caribaea and P. oocarpa. The Wilgeboom trial was 16 months older and growing conditions were more favourable at that site but the magnitude of the differences in DEN, VAR, VUB and DMI would suggest that a portion of these differences could be attributed to species. In terms of wood density and volume, provenances of P. patula ssp. tecunumanii would be preferred to the other species tested at these two sites.

KwaMbonambi, South Africa

The trials at KwaMbonambi were adjacent and included a local

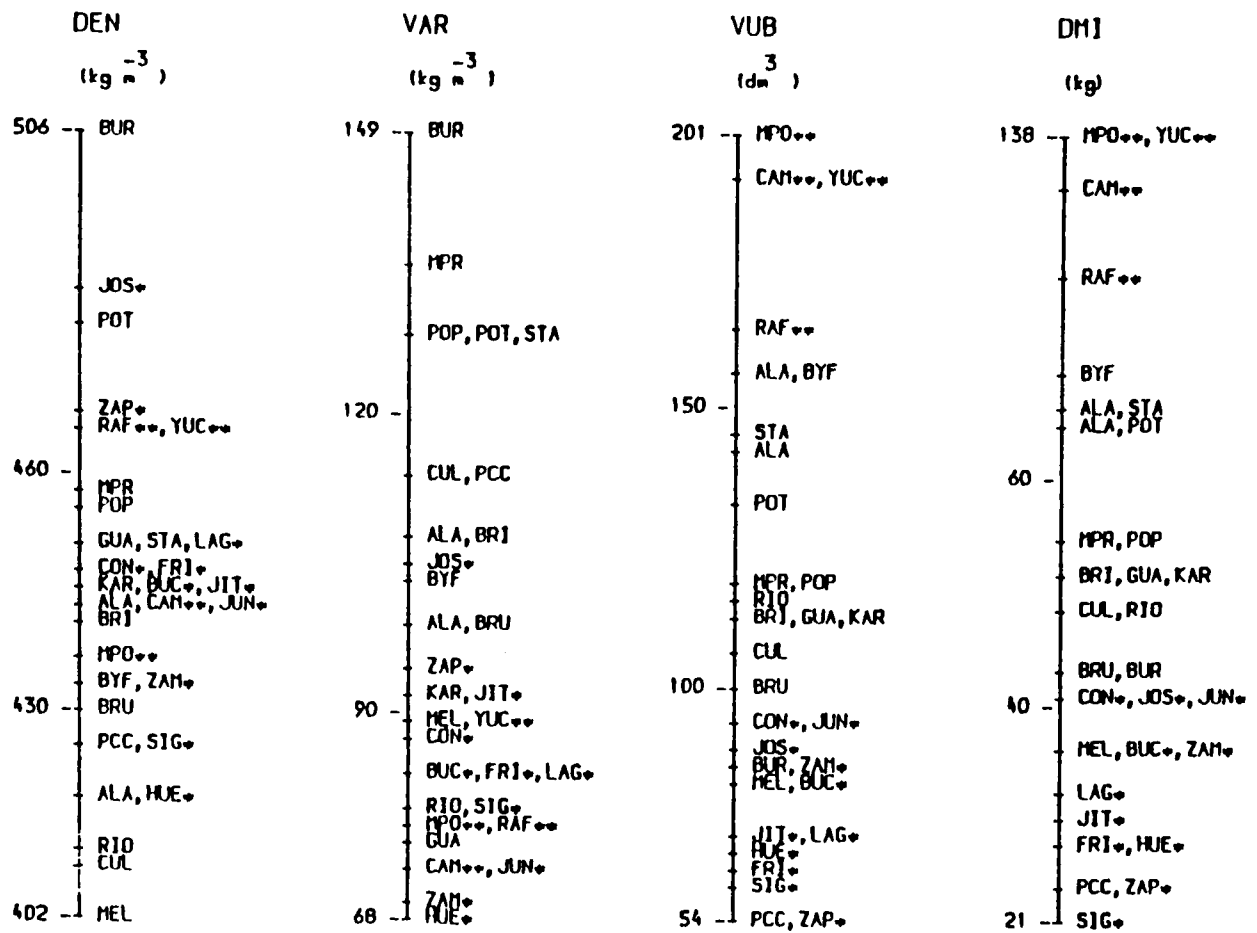


FIGURE 2.22 Comparison of provenance means from *P. caribaea*, *P. oocarpa* (*) and *P. patula* ssp. *tecunumanii* (**) for densitometric density (DEN), within sample density variation (VAR), volume under bark (VUB) and dry matter Index (DMI) at Anasco, Puerto Rico.

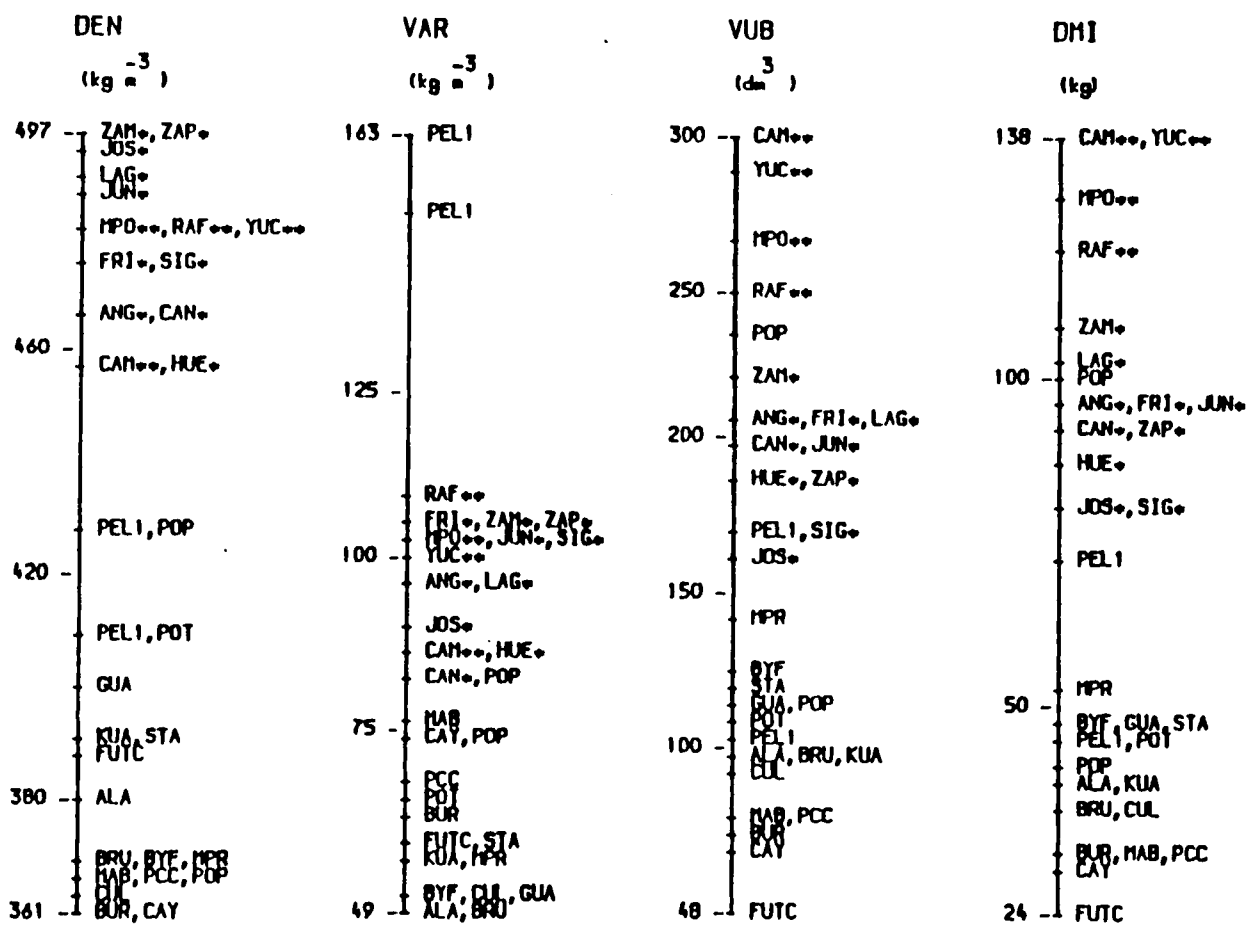


FIGURE 2.23 Comparison of provenance means from *P. caribaea*, *P. oocarpa* (*) and *P. patula* ssp. *tecunumanii* (**) for densitometric density (DEN), within sample density variation (VAR), volume under bark (VUB) and dry matter Index (DMI) in the Eastern Transvaal, South Africa.

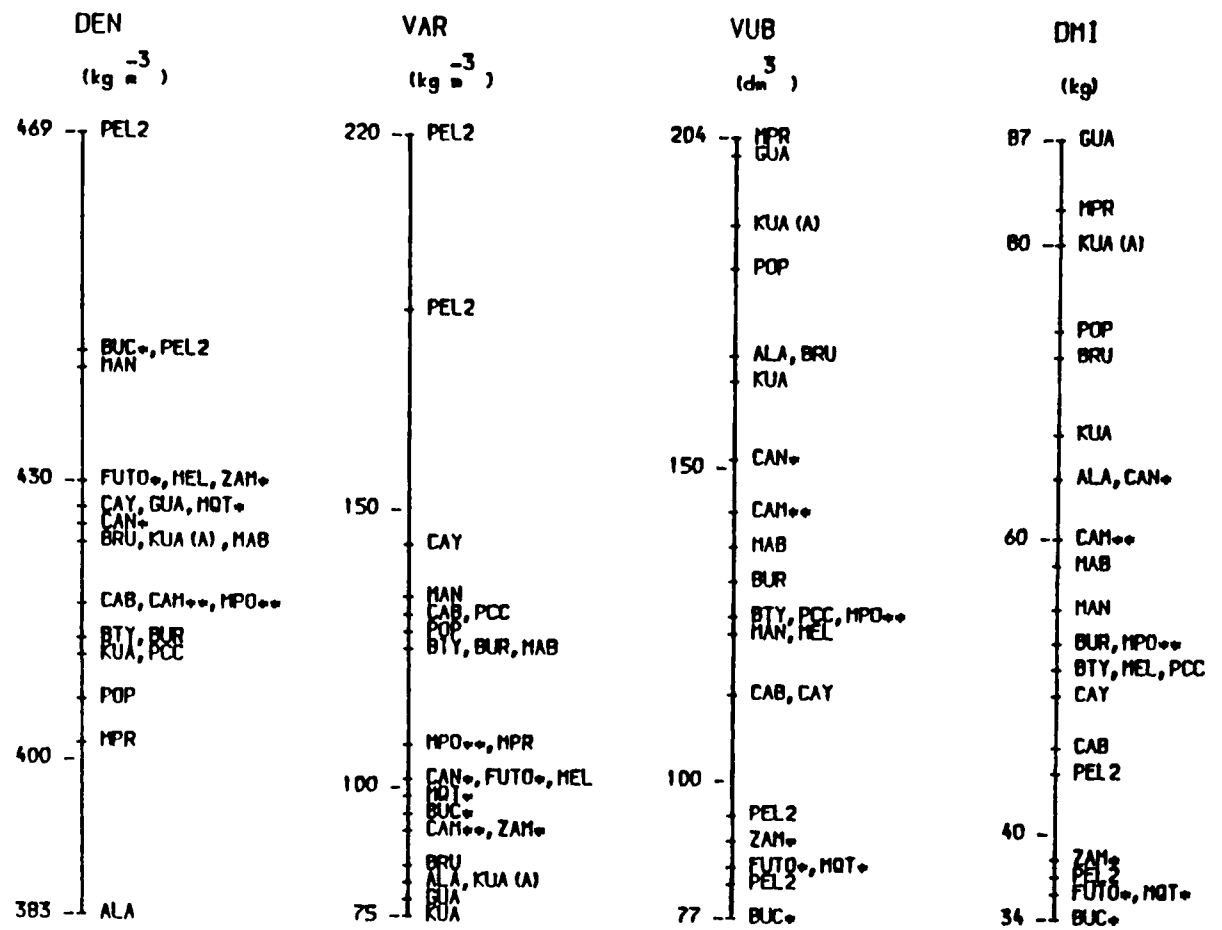


FIGURE 2.24 Comparison of provenance means from *P. caribaea*, *P. oocarpa* (*) and *P. patula* ssp. *tecunumanii* (***) for densitometric density (DEN), within sample density variation (VAR), volume under bark (VUB) and dry matter Index (DMI) in Zululand, South Africa.

source of P. elliotii. The results of the ANOVA for the P. caribaea trial are in Figure 2.7 and are in Figure 2.20 for the P. oocarpa and P. patula ssp. tecunumanii. The two trials are compared in Figure 2.24. Trial mean values for DEN and VAR were similar for provenances of P. caribaea var. caribaea, P. oocarpa and P. patula ssp. tecunumanii. The values of DEN and VAR for provenances of P. caribaea var. hondurensis were generally lower while the highest values for DEN and VAR in both trials were for P. elliotii. Lückhoff (1964) also observed in South Africa that wood of P. caribaea had greater uniformity than wood of P. elliotii. The provenances Guanaja and Mountain Pine Ridge of P. caribaea produced more VUB and DMI than the other varieties of this species and were also higher than provenances of P. oocarpa and P. patula ssp. tecunumanii for these two traits. The results of these trials indicate that P. caribaea var. hondurensis would be the preferred species unless wood density has to be above a critical minimum level.

Conclusion

The comparison of provenances of P. caribaea, P. oocarpa and P. patula ssp. tecunumanii indicate that large gains in DEN, VUB and DMI are possible when the correct seed source is planted on the correct site. The DEN of P. oocarpa and P. patula ssp. tecunumanii provenances were equal or superior to the DEN of P. caribaea provenances at these three locations. If an organization requires wood of high density then it should favour provenances from the former two species. The final choice of species and provenance for plantation establishment should only be made when replicated trials have indicated those genetic sources that are best for the end use product.

2.4 Visual assessment of variation in wood density across sites and provenances

The analysis of individual trials indicated certain sites and

provenances that were interesting from the standpoint of the relative values of DEN and VAR. A sub-set of increment cores from these sites and provenances (Table 2.4) were therefore selected for visual assessment of the densitometric trace. Provenances and sites were chosen so as to include a group of provenances that had either high or low VAR at a number of sites. For inclusion in the sub-set, the increment cores had to have a low percentage of compression wood and the pith had to be visible. In addition, no broken or fractured increment cores were chosen. The best two cores which met all of the criteria were chosen. The densitometric trace for the increment cores are presented in Appendix 1. Each provenance was represented by increment cores from two trees but due to the selection criteria of site, provenance and increment core this sub-set can not be considered a random sample. All values of the correlation coefficients referred to are from Table 3.9.

The densitometric traces revealed large differences in VAR between sites, provenances, trees and radii. In P. caribaea, high VAR was likely due to a higher percentage of high density wood since the increment cores seldom had a wood DEN of less than 0.3g cm^{-3} . Also, there appeared to be more high density wood as one moved away from the pith. This would suggest that VAR will increase as tree age increases and could explain the high correlation ($r=0.600$) between VAR and site age in this species. The width of the band of high density wood seems to be of critical importance in determining VAR. For example, Tree 5040A of the Poptun provenance at San Pedro (Figure 1.4) had very wide bands of high density wood and had the highest VAR at that site.

Increment cores from provenances of Alamicamba and Guanaja were much more uniform in DEN than those from the Mountain Pine Ridge and Poptun provenances. This was likely due to the lower percentage of wood of higher density in Alamicamba and Guanaja. Also, increment cores of Guanaja were found to contain high density wood only in the outermost portion of the radii. The high

correlation ($r=0.833$) of VAR with provenance altitude would agree with the visual assessment since Alamicamba and Guanaja are from low altitude. The inland sources of P. caribaea, Mountain Pine Ridge and Poptun, more closely resembled P. elliottii than did the coastal provenances.

Table 2.4 Sites and provenances sampled for visual assessment of within sample density variation.

Species	Site	Provenances
<u>P. caribaea</u>	San Pedro	Alamicamba, Guanaja, Mountain Pine Ridge, Poptun
	Mariti	Alamicamba, Guanaja, Mountain Pine Ridge, <u>P. elliottii</u> , Poptun
	KwaMbonambi	Alamicamba, Guanaja, Mountain Pine Ridge, <u>P. elliottii</u> , Poptun
	Bukit Tapah	Alamicamba, Guanaja, Mountain Pine Ridge, <u>P. elliottii</u> , Poptun
<u>P. oocarpa</u> / <u>P. patula</u> ssp. <u>tecunumanii</u>	Conocoto	Camelias, Huehuetenango, Zamorano
	Wilgeboom	Camelias, Huehuetenango, Mountain Pine Ridge, <u>P. elliottii</u> , Zamorano
	KwaMbonambi	Camelias, Mountain Pine Ridge, <u>P. elliottii</u> , Zamorano
	Nzoia	Camelias, Huehuetenango, Mountain Pine Ridge, Zamorano

The P. elliottii source had a much higher VAR at Mariti and KwaMbonambi than any of the P. caribaea provenances and this was probably due to the larger difference in high and low density wood of this species relative to P. caribaea. Increment cores of P. elliottii had wide bands of high density wood at these two sites. This species also exhibited the greatest regularity of growth rhythm of any of the increment cores evaluated.

The differences between provenances at Mariti and KwaMbonambi are of special interest due to the difference in altitude (993m) and growing conditions between these trials. At Mariti, the four provenances of P. caribaea were much lower in VAR than the same provenances grown at KwaMbonambi. The wider bands of high density wood at KwaMbonambi may result from rainfall and temperature patterns which allow the trees to grow during the winter at this

site, albeit at a greatly reduced rate. Wood produced during these periods of reduced rainfall, temperature and sunlight would likely have thicker cell walls, smaller lumen width and hence higher VAR.

In P. oocarpa and P. patula ssp. tecunumanii, VAR also seemed to depend on the width of high density wood. The densitometric traces from P. patula ssp. tecunumanii increment cores had regular peaks of high density wood but these did not have the height or width of P. elliottii and P. caribaea. The Huehuetenango provenance of P. oocarpa, was low for VAR at most of the sites in which it was planted. The densitometric trace of increment cores of this provenance show very small bands of high density wood and this could have resulted in low VAR. By contrast, the P. elliottii grown at Wilgeboom and KwamBonambi had wide bands of high density wood and hence high VAR. The Mountain Pine Ridge provenance of P. patula ssp. tecunumanii had slightly wider bands of high density wood than Camelias and was higher for VAR.

The two sites of P. oocarpa and P. patula ssp. tecunumanii at low latitude, Conocoto and Ecuador, were the lowest for VAR of any trial in this study and thus could partly explain the high correlation ($r=0.896$) between VAR and site latitude for these species. The densitometric traces from increment cores taken at these sites show very narrow bands of high density wood and this could have resulted in low VAR. There were two peaks per year for the increment cores at these sites and this would be expected given the two rainy periods per year. Brown (1970) stated that there was no evidence supporting photoperiodic control of latewood production under natural conditions. However, the data and densitometric traces from this study would suggest that trees of P. oocarpa and P. patula ssp. tecunumanii growing near the equator are uniform in DEN because there is no change in photoperiod to stimulate a change to thicker cell walls and/or reduced lumen width.

Differences between species were more difficult to assess because there was only one site (KwaMbonambi) where the trials were planted side-by-side and this site would be considered more suitable for P. caribaea. However, the densitometric traces from the Mountain Pine Ridge provenance of P. patula ssp. tecunumanii, Zamorano of P. oocarpa, and the Mountain Pine Ridge and Poptun provenances of P. caribaea do resemble each other. The similarity in VAR of these four provenances could be due to the fact that they are from areas of high altitude and thus respond in a similar manner to the growing conditions at KwaMbonambi.

When grown under similar environmental conditions in the Eastern Transvaal, provenances of P. oocarpa and P. patula ssp. tecunumanii had much wider bands of high density wood than did provenances of P. caribaea and could explain the lower values of VAR for the latter. It should be noted, however, that the sites sampled in the Eastern Transvaal would not normally be considered as ideal sites for P. caribaea and this could bias the species comparison.

Conclusion

The visual assessment of VAR from densitometric traces reveal large differences between sites, provenances, trees and radii. An organization could vary VAR by careful selection of site and genotype. High values of VAR seem to be the result of an increased frequency of higher density wood. Trees with low VAR show very little difference in wood density from pith to bark. Any combination of genetic sources, silvicultural techniques or climatic factors that result in wide bands of high density wood will result in trees of high VAR.

3 ANALYSIS OF GENOTYPE BY ENVIRONMENT INTERACTION

The trials included in the analysis of genotype by environment interaction (GEI) were selected to represent a range of environments. The provenances were selected so that the most orthogonal set of provenances across sites would be included in the analysis (Figures 3.1 to 3.4). Only provenances of P. caribaea var. hondurensis were included in the GEI analysis of those trials since provenances of the other varieties were not included at sufficient trial sites. Certain species and provenances have therefore been evaluated in environments where they are not normally considered to be financially or biologically suited. Further discussion of the site and provenance selection process can be found in Gibson (1982). The data for VUB and DMI was not assessed for GEI but results for a subset of sites and provenances of P. caribaea for VUB are discussed by Gibson et al. (1983).

Bartlett's Test (Snedecor and Cochran, 1980) was used before the GEI analysis to determine if the residual variances of the individual trials were sufficiently homogeneous. If the residual variances are heterogeneous, significant treatment effects could occur with greater frequency than would be expected. Gibson (1982) found that "Virtually all traits analysed show significant differences in error variance between experiments". The Bartlett's Test on the residual variances of DEN and VAR from the two series of trials indicated that these variances were significantly different (Table 3.1). This indicates that treatment effects tested against the pooled residual variance in the F test may be in doubt if they are slightly above the tabular statistical levels (Cochran and Cox, 1957).

Table 3.1 Bartlett's Test for homogeneity of the residual variance for DEN and VAR of trials and provenances selected for GEI analysis.

Species	Trait	df	Chi square	Probability
<u>P. caribaea</u>	DEN	10	190.6	p<0.001
	VAR	10	248.3	p<0.001
<u>P. oocarpa</u> and	DEN	5	53.5	p<0.001
<u>P. patula</u> ssp. <u>tecunumanii</u>	VAR	5	62.7	p<0.001

3.1 Description of the statistical methods used

For the selected provenances and sites, provenance block means for DEN and VAR were analyzed using the analysis of variance (ANOVA). The model used was:

$$\text{DEN}_{sp} \text{ or } \text{VAR}_{sp} = \mu + B_{b(s)} + S_s + P_p + SP_{sp} + E_{sp}$$

where DEN_{sp} or VAR_{sp} is the value of the s^{th} site and the p^{th} provenance, μ is the population mean, $B_{b(s)}$ is the effect of the b^{th} block in the s^{th} site, S_s is the effect of the s^{th} site, P_p is the effect of the p^{th} provenance, SP_{sp} is the interaction of the s^{th} site and the p^{th} provenance and E_{sp} is the residual.

A mixed model was used with blocks as random effects and with sites and provenances as fixed effects. The provenances and sites in the GEI analysis were chosen to permit analysis of an orthogonal set of provenances across sites and represent only a portion of the densitometric data derived from all trials. The provenances were not sampled with the intention of representing the entire range of the species and were therefore a fixed effect. Also, the provenances referred to in the GEI analysis of DEN and VAR represent only the trees from which the seed was

originally collected and should therefore be considered a fixed effect. Sites are also a fixed effect since the wood densitometric values are indicative of the soil and climatic factors that affected the trees from the time of planting until the time of sampling. It would be statistically incorrect to make inferences from these analyses about sites or provenances that were not included. However, it may be that the results reported here can be used by a cautious pragmatist to suggest likely values for DEN and VAR of a given provenance at a given site.

The form of the ANOVA and the expectation of mean squares are given in Table 3.2. For DEN and VAR, the Scheffé's test was used to determine if there were significant differences between the inland and coastal groups of P. caribaea or between P. oocarpa and P. patula ssp. tecunumanii.

Table 3.2 Analysis of variance and expectation of mean squares for the GEI assessment.

Source	df	Expectation of mean squares
Sites	s-1	$\sigma^2_e + ps\sigma^2_{b(s)} + pb\sigma^2_s$
Blocks in sites	s(b-1)	$\sigma^2_e + ps\sigma^2_{b(s)}$
Provenances	p-1	$\sigma^2_e + sb\sigma^2_p$
Site x provenance	(s-1)(p-1)	$\sigma^2_e + b\sigma^2_{sp}$
Residual	s(b-1)(p-1)	σ^2_e
Total	sbp-1	

The unequal number of blocks between locations (Table 1.1) had no effect on the calculation of df since this term was derived by summation. For the calculation of the variance components, however, a "corrected" value of b was derived using the method of Ganguli (1941).

The formula used to derive b was:

$$b = \frac{1}{a-1} \left(N - \frac{\sum_{i=1}^n n_i^2}{N} \right)$$

where a is the number of sites, N is the total number of blocks, and n_i is the number of blocks at the i^{th} site. For P. caribaea, the value of b was calculated to be 5.55 and for P. oocarpa and P. patula ssp. tecunumanii b was 4.11.

3.2 P. caribaea

The ANOVA revealed significant differences between sites and provenances for both DEN and VAR and these two terms accounted for most of the variance due to treatments (Table 3.3). The site by provenance interaction term was not significant and accounted for none of the variance. Despite the significant differences between the residual variances in DEN and VAR as indicated by the Bartlett's Test, the low F ratio of site by provenance interaction and the high F ratio for provenances suggest that the pooled residual variances were acceptable for testing these sources. Sites accounted for more of the variance in DEN and VAR than did provenances and Gibson (1982) also observed this for certain traits in P. caribaea. The low variance accounted for by provenance would be due to large within provenance differences. In DEN, most of the variance was accounted for by the residual (66.8%) but for VAR most of the variance was accounted for by sites (57.7%).

The significant differences in DEN and VAR between sites could be the result of differences in age, rainfall, temperature or the interaction of these climatic characteristics. However, the Byfield, San Pedro, Bukit Tapah, Anasco-A and Drasa trials were clearly higher for DEN. For VAR, the highest trial means were observed at Loudima and San Pedro. The lowest values for DEN and VAR were at Chati and Mariti which were the P. caribaea sites with the highest altitude. The effects of experimental site

characteristics on DEN and VAR are discussed in section 3.4 of this chapter.

Table 3.3 Analysis of variance of plot means from eleven provenances of P. caribaea at eleven sites for DEN and VAR.

Source	df	MS		VC (%)		F	
		DEN	VAR	DEN	VAR	DEN	VAR
Site	10	0.0662	0.0777	28.9	57.7	24.1***	82.9***
Blocks in Sites	51	0.0028	0.0009	0.1	0.1	1.1	1.2
Provenance	10	0.0107	0.0130	4.2	5.5	4.5***	16.7***
SitexProvenance	87(13)	0.0016	0.0008	0.0	0.0	0.7	1.0
Residual	463(47)	0.0024	0.0008	66.8	36.7		
Total	621						

The provenance mean values for DEN and VAR at the eleven sites are presented in Figures 3.1 and 3.2, respectively. The Scheffés test revealed no significant differences in DEN or VAR between the inland and coastal groups of P. caribaea (Figure 3.5). However, the coastal provenances of P. caribaea, Alamicamba, Brus Lagoon, Karawala and Rio Coco were generally ranked below the trial mean for DEN and VAR while the inland provenances, Potosi and Santa Clara were generally ranked above the trial mean for these traits. The insular provenance, Guanaja, of P. caribaea ranked among the highest for DEN and the lowest for VAR across the eleven sites while the Poptun provenance was ranked the highest for VAR at seven of the ten sites in which it was planted. The effects of provenance origin on DEN and VAR are discussed in section 3.4 of this chapter.

Conclusion

The large variance accounted for by site would suggest that tree breeders and forest managers should be very concerned with sites chosen for afforestation with P. caribaea if wood density is important for the intended end product. At a given site, there would probably be numerous provenances which would have



FIGURE 3.1 Density (kg m⁻³) of eleven provenances of *Pinus caribaea* var. *hondurensis* at eleven sites.

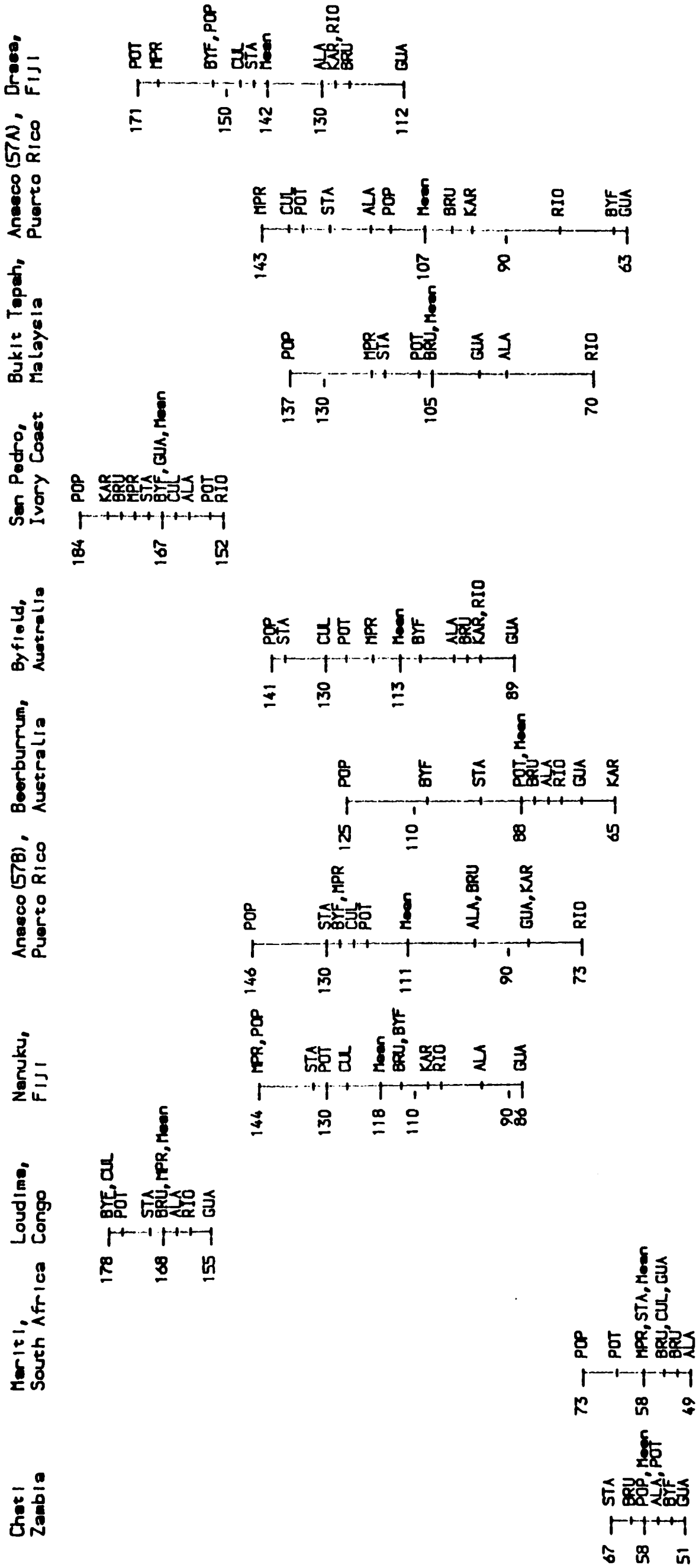


FIGURE 3.2 Within sample density variation (kg m^{-3}) of eleven provenances of *Pinus caribaea* var. *hondurensis* at eleven sites.

acceptable mean density values. Within a provenance, there would normally be large tree-to-tree differences for wood density as well as for volume and form. Individual trees within "superior" provenances could therefore be chosen which were superior for DEN, VAR, volume and form.

3.3 P. oocarpa and P. patula ssp. tecunumanii

The ANOVA revealed significant differences between sites and provenances (Table 3.4) and these two terms accounted for most of the variance. The site by provenance interaction term was not significant and accounted for none of the variance. As with P. caribaea var. hondurensis, the low F ratio of the site by provenance interaction term would suggest that the use of the pooled residual variances was acceptable for testing this source. In DEN, the residual term accounted for most of the variance (69.4%) whereas for VAR most of the variance was accounted for by sites. This was similar to the pattern observed in P. caribaea. The low variance accounted for by provenance would have been due to large differences in DEN and VAR within provenances.

Table 3.4 Analysis of variance of plot means from five provenances of P. oocarpa and four provenances of P. patula ssp. tecunumanii at six sites for DEN and VAR.

Source	df	MS		VC (%)		F	
		DEN	VAR	DEN	VAR	DEN	VAR
Site	5	0.0171	0.0103	24.5	56.6	6.3***	174***
Blocks in sites	19	0.0027	0.00006	2.0	0.0	2.5**	0.3
Provenance	8	0.0026	0.0005	4.1	2.5	2.4*	2.5*
Sitexprovenance	35(5)	0.0011	0.0002	0.0	0.0	1.0	1.0
Residual	130(22)	0.0011	0.0002	69.4	40.9		
Total	197						

Differences in site means for DEN and VAR could be due to different ages, rainfall or temperature patterns. The Conocoto and Agudos sites had the highest values of DEN. For VAR, the

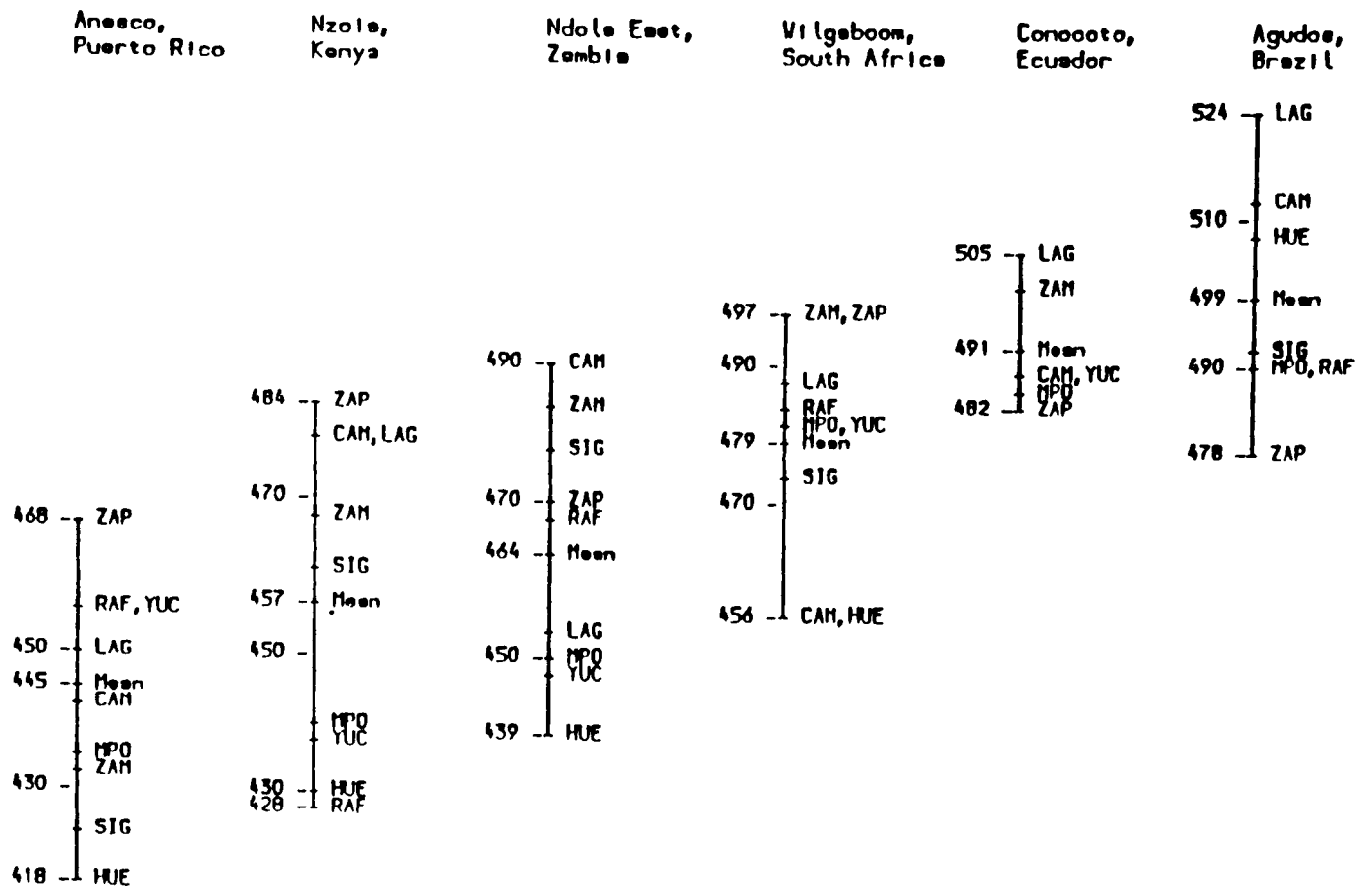


FIGURE 3.3 Density (kg m^{-3}) of five provenances of *Pinus oocarpa* and four provenances of *P. patula* ssp. *tecunumanii* at six sites.

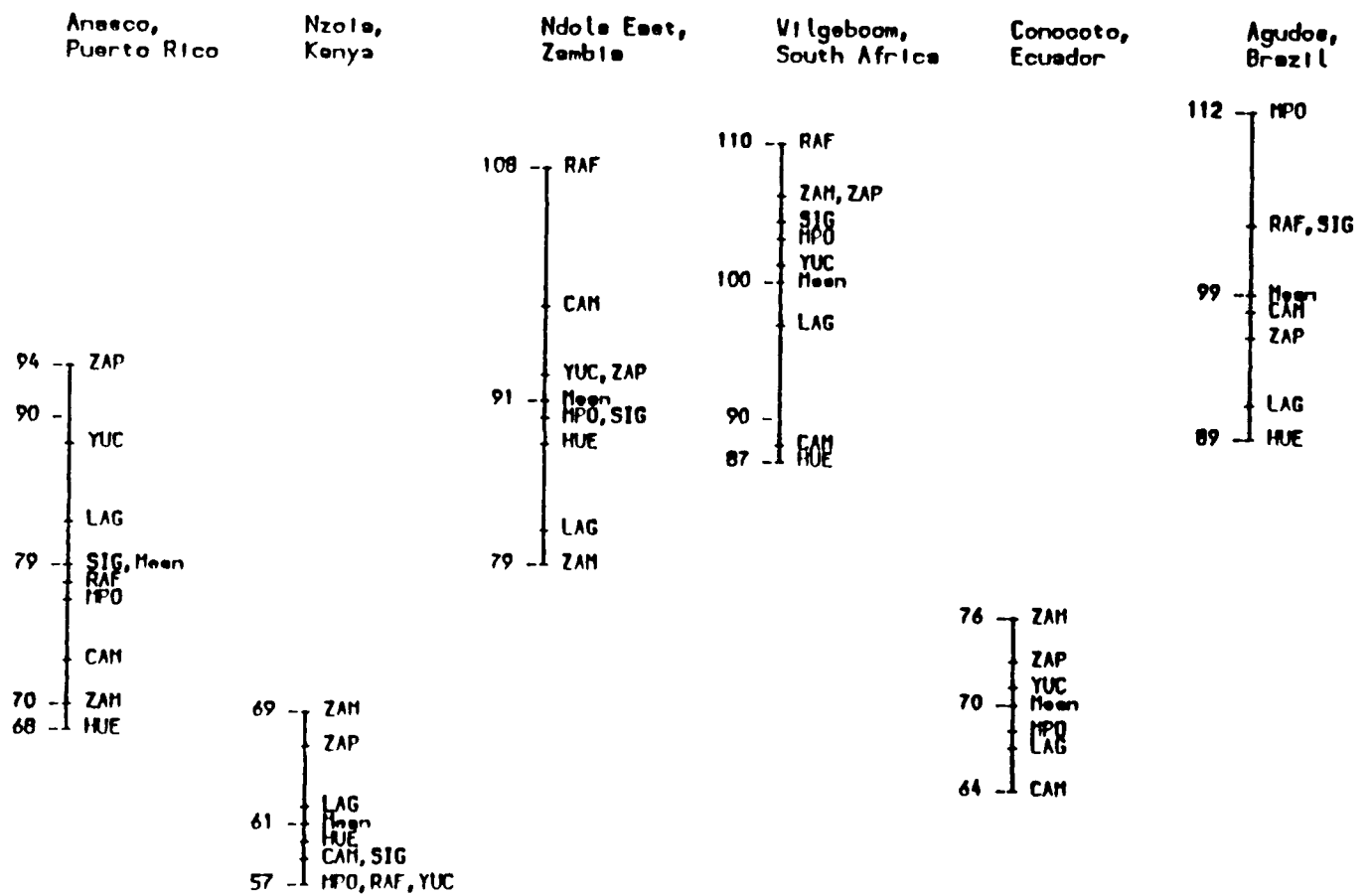


FIGURE 3.4 Within sample density variation (kg m^{-3}) of five provenances of *P. oocarpa* and four provenances of *P. patula* ssp. *tecunumanii* at six sites.

Wilgeboom and Agudos sites had the highest values. The lowest values for VAR were observed at Nzoia and Conocoto and these two trials were at the lowest latitude of any P. oocarpa and P. patula ssp. tecunumanii trial. The effect of experimental site characteristics on DEN and VAR will be discussed in section 3.4 of this chapter.

Provenance ranking across the P. oocarpa and P. patula ssp. tecunumanii trials was inconsistent. This was due to the fact that provenances were significantly different for DEN and VAR at only one of the six sites evaluated. The Scheffés test revealed no significant differences in DEN and VAR between P. oocarpa and P. patula ssp. tecunumanii (Figure 3.5). However, the Huehuetenango provenance of P. oocarpa was ranked consistently low for DEN and VAR. The effect of provenance origin on DEN and VAR will be discussed in section 3.4 of this chapter.

Conclusion

As with P. caribaea, careful attention should be given to site selection for afforestation with P. oocarpa and P. patula ssp. tecunumanii if wood density is important for the intended end product. The corrected provenance means across sites (Figure 3.5) indicated that P. caribaea provenances had lower DEN and higher VAR than did provenances of P. oocarpa and P. patula ssp. tecunumanii. This would suggest that a forest manager must be more discriminating when choosing sites for P. caribaea since wood of low density may not be acceptable as a raw material for pulp, paper or structural use.

3.4 The effect of experimental site and provenance origin parameters on DEN and VAR

From the P. caribaea GEI analysis, it was observed that DEN and VAR were to a certain extent affected by experimental site. In P. oocarpa and P. patula ssp. tecunumanii, VAR seemed to vary as

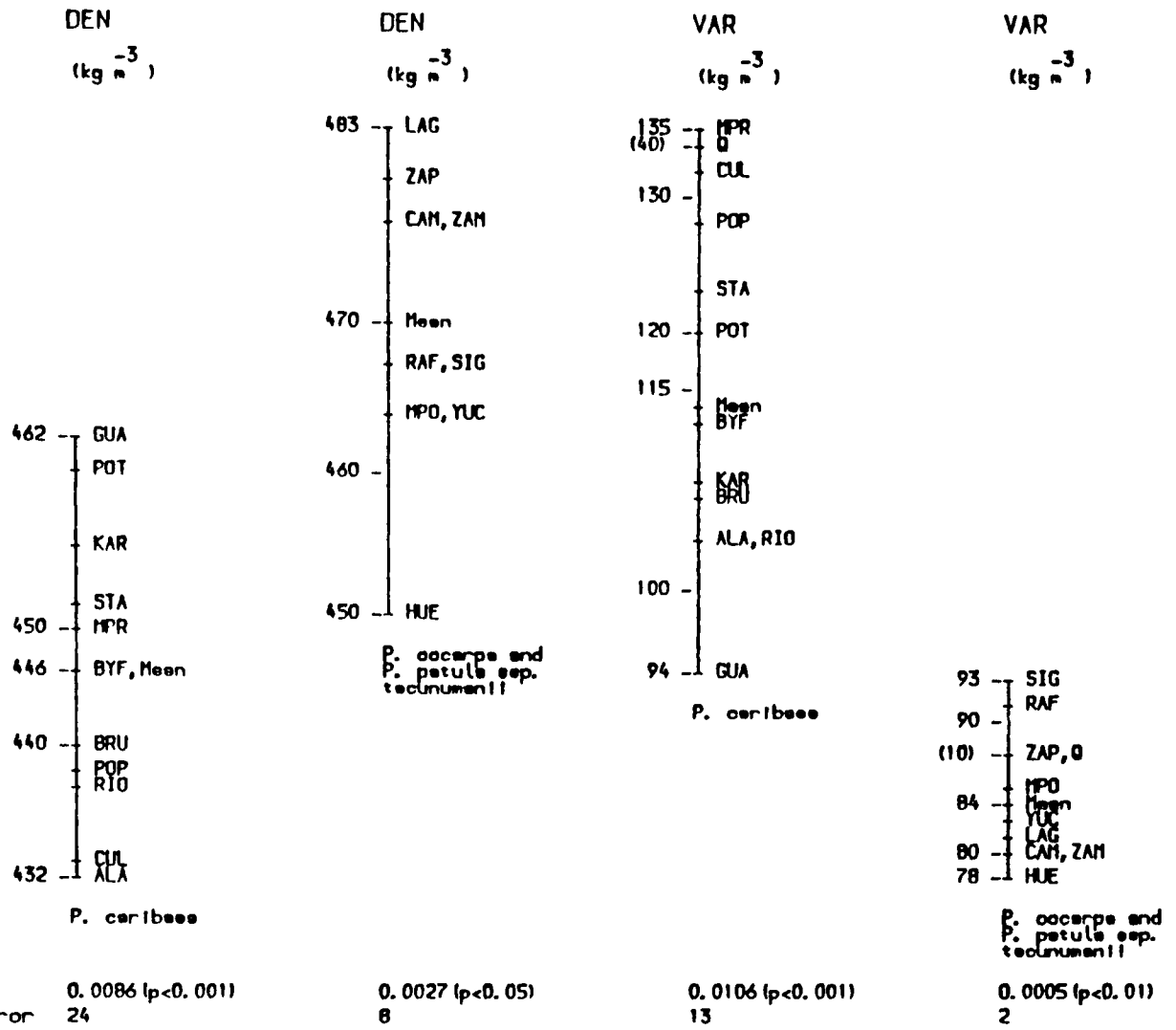


FIGURE 3.5 Corrected mean values of DEN and VAR and the critical difference, Q, at the 5% level for provenances of *P. caribaea* at eleven sites and provenances of *P. oocarpa* and *P. patula* ssp. *tecunumanii* at six sites.

a result of the site. Since altitude and latitude affect the patterns of rainfall, temperature and photoperiod, the relative contribution of climatic and geographic parameters due to experimental site and provenance origin were determined in order to evaluate their importance in influencing DEN and VAR. The lack of significance in the site by provenance interaction term for DEN and VAR indicated that site means corrected for provenances and provenance means corrected for sites could be used. The use of corrected values for provenance and site means overcomes any possible bias due to unequal numbers of blocks between sites. It also greatly reduces the number of degrees of freedom. The corrected site and provenance means are presented in Appendix 2.

The most important parameters due to experimental site and provenance origin (Tables 1.2, 1.3 and 1.4) were evaluated. Data for rainfall and temperature were often gathered some distance from the trial site or provenance collection location and extrapolated values have been used in these analyses. As a general rule, the data from experimental site was considered to be more accurate than the data from provenance origin. The indication of variation in DEN and VAR due to experimental site or provenance origin characteristics could assist forest managers and tree breeders in their afforestation programmes with these species. Corrected site and provenance means for DEN and VAR were regressed on individual climatic and geographic parameters as well as on realistic groups of these parameters. The model used for sites was:

$$\text{DEN}_s \text{ or } \text{VAR}_s = \alpha_0 + \alpha_L + \alpha_A + \alpha_R + \alpha_T + \alpha_M + \epsilon_s$$

where DEN_s or VAR_s is the S^{th} site mean corrected for provenances, α_0 is the population mean, $\alpha_L, \alpha_A, \alpha_R, \alpha_T$ and α_M are the latitude, altitude, rainfall, temperature and age in months of the s^{th} site, respectively, and ϵ_s is the residual. The model used for provenances was:

$$\text{DEN}_p \text{ or } \text{VAR}_p = \alpha_0 + \alpha_L + \alpha_A + \alpha_R + \alpha_T + \epsilon_P$$

where DEN_s or VAR_p is the P^{th} provenance mean corrected for sites, α_0 is the population mean, $\alpha_L, \alpha_A, \alpha_R$ and α_T are the latitude, altitude, rainfall and temperature of the p^{th} provenance, respectively, and ϵ_P is the residual. The mean squares and the squared multiple correlation coefficient (R^2) are given in Tables 3.5 to 3.8. The multiple correlation coefficient was calculated by dividing the sum of squares due to regression by the total sum of squares and thus represents the reduction in the sum of squares due to regression (Anderson and Bancroft, 1952). The correlations of DEN and VAR with the climatic and geographic parameters are summarized in Table 3.9 and the full correlation matrices are contained in Appendix 3.

Table 3.5 Comparison of regression models used to fit the site mean of DEN and VAR due to experimental site parameters in P. caribaea.

Model (df regression)	MS (regression)		MS (residual)		R ² (%) (regression)	
	DEN	VAR	DEN	VAR	DEN	VAR
	1. SL + SA + SR + ST + SM(5)	2409**	2757**	198	82	92.4
2. SL + SA + SR + ST(4)	2930*	3290**	218	173	89.9	92.7
3. SL + SA + SR(3)	3905**	4387**	188	148	89.9	92.7
4. SL + SA + ST(3)	3551**	4299**	340	186	81.7	90.8
5. SL + SA + SM(3)	3888**	4576**	196	67	89.5	96.7
6. SA + SR + ST(3)	3853**	3639*	211	468	88.7	76.9
7. SL + SA(2)	5285**	6440**	308	165	81.1	90.7
8. SA + ST(2)	5276**	5254**	310	461	81.0	74.0
9. SA + SR(2)	5622**	4044*	224	764	86.3	57.0
10. SR + ST(2)	3814*	4705*	676	598	58.5	66.3
11. SL(1)	554	4584	1387	1068	4.3	32.3
12. SA(1)	9904**	8013**	348	687	76.0	56.4
13. SR(1)	2654	28	1153	1574	20.3	0.2
14. ST(1)	6682*	8976**	706	580	51.2	63.2
15. SM(1)	10	5114	1447	1009	0.1	36.0

The largest multiple correlation coefficient calculated from

fitting a single variable regression in DEN of P. caribaea was due to site altitude. For VAR, the regression equation that included site latitude, altitude and age accounted for almost as much of the total sum of squares as the model which included the terms of site rainfall and temperature. For DEN, the high multiple correlation coefficient of site altitude would confirm the findings of Barnes et al. (1977).

None of the regression equations accounted for more than 55.3% of the total sum of squares in DEN of P. oocarpa and P. patula ssp. tecunumanii. For VAR, the largest per cent of the total sum of squares (98.8%) was accounted for by the regression equation which included site latitude, altitude, rainfall and temperature though site latitude alone accounted for 80.2%.

The differences in the per cent reduction in the sum of squares due to regression of the climatic and geographic characteristics suggest that the species are not affected by these characteristics in the same way. This would be expected since the species are themselves indigenous to areas with different rainfall and temperature patterns. For instance, the mean annual rainfall and temperature in the P. caribaea provenances are higher than those of P. oocarpa and P. patula ssp. tecunumanii provenances. While one can probably say with confidence that these species will respond differently to the patterns of rainfall, temperature and photoperiod it is more difficult to say what, if any, would have been the selective advantage in the indigenous stands of high or low DEN and VAR in an individual tree.

None of the regression equations for provenance origin parameters of P. caribaea accounted for more than 24.6% of the total sum of squares in DEN. The low values of the multiple correlation coefficient would have been expected given the low F ratio (4.5) for this trait. For VAR, the sum of squares due to regression by provenance temperature (74.4%) only slightly exceeded that accounted for by provenance altitude (69.3%). In P. caribaea, the

inland provenances have been observed to have higher density than coastal provenances (Garcia de Leon, 1982; Barnes *et al.*, 1983). The trends from this analysis would indicate that VAR is more closely associated with provenance altitude than DEN especially since the Guanaja provenance is from low altitude but was consistently low for VAR whereas the Poptun provenance is from high altitude and was consistently high for VAR.

Table 3.6 Comparison of regression models used to fit the site mean of DEN and VAR due to experimental site parameters in *P. oocarpa* and *P. patula* ssp. *tecunumanii*.

Model (df regression)	MS (regression)		MS (residual)		R ² (%) (regression)	
	DEN	VAR	DEN	VAR	DEN	VAR
1. SL + SA + SR + ST + SM(5)	424	262	0 ¹	0 ¹	-	-
2. SL + SA + SR + ST(4)	294	324	948	15	55.3	98.8
3. SL + SA + SR(3)	385	413	484	36	54.4	94.5
4. SL + SA + ST(3)	386	399	482	56	54.6	91.5
5. SL + SA + SM(3)	362	400	518	55	51.2	91.6
6. SA + SR + ST(3)	386	362	482	112	54.6	82.9
7. SL + SA(2)	542	597	346	39	51.0	91.1
8. SA + ST(2)	576	535	323	80	54.3	81.8
9. SA + SR(2)	291	387	513	178	27.4	59.2
10. SR + ST(2)	325	125	491	353	30.6	19.0
11. SL(1)	83	1050*	510	65	3.9	80.2
12. SA(1)	95	422	507	222	4.5	32.2
13. SR(1)	570	25	388	321	26.9	1.9
14. ST(1)	540	49	395	315	25.4	3.7
15. SM(1)	124	31	499	320	5.8	2.4

¹The SS due to the residual was zero since the regression uses all of the degrees of freedom from the total.

Table 3.7 Comparison of regression models used to fit the mean provenance values of DEN and VAR to provenance origin parameters in P. caribaea.

Model (df regression)	MS (regression)		MS (residual)		R ² (%) (regression)	
	DEN	VAR	DEN	VAR	DEN	VAR
1. PL + PA + PR +PT(4)	172**	405*	24	94	24.6	77.6
2. PL + PA + PR(3)	135	520	76	86	24.5	74.8
3. PL + PA + PT(3)	137	539*	213	88	23.3	77.6
4. PA + PR + PT(3)	118	534*	223	81	21.0	76.8
5. PL + PA(2)	63	770**	110	78	24.2	73.9
6. PL + PR(2)	65	587*	109	130	20.2	56.3
7. PL + PT(2)	193	800*	187	69	22.8	76.7
8. PA + PR(2)	170	732*	193	89	20.1	70.1
9. PA + PT(2)	154	781*	198	75	18.2	74.8
10. PR + PT(2)	177	800*	191	69	20.9	76.7
11. PL(1)	181	273	189	227	10.7	13.1
12. PA(1)	300	1446**	174	80	17.8	69.3
13. PR(1)	322	1167*	171	115	19.1	55.9
14. PT(1)	295	1552**	175	67	17.5	74.4

In P. oocarpa and P. patula ssp. tecunumanii, the regression equations accounted for a larger per cent of the total sum of squares for DEN than for VAR and this contrasts with P. caribaea where the reverse was true. The lack of significant differences between provenances within sites for these species would, however, indicate that these results be viewed with caution.

The correlations of DEN and VAR with climatic and geographic characteristics were higher for P. caribaea than for P. oocarpa and P. patula ssp. tecunumanii. The mean DEN from sites of P. caribaea was positively and significantly correlated with site temperature as was VAR. DEN and VAR were negatively and significantly correlated with site altitude. VAR was found to be positively and significantly correlated with provenance altitude. Provenance rainfall and temperature were found to be negatively and significantly correlated with the mean VAR of a provenance. In P. oocarpa and P. patula ssp. tecunumanii, the only

significant correlation was between site latitude and the site mean of VAR. This correlation was positive.

Table 3.8 Comparison of regression models used to fit mean provenance values of DEN and VAR to provenance origin parameters in P. oocarpa and P. patula tecunumanii.

Model (df regression)	MS (regression)		MS (residual)		R ² (%) (regression)	
	DEN	VAR	DEN	VAR	DEN	VAR
	1. PL + PA + PR + PT(4)	172	19	25	16	87.5
2. PL + PA + PR(3)	135	23	76	14	51.4	50.0
3. PL + PA + PT(3)	102	18	96	17	39.1	38.6
4. PA + PR + PT(3)	184	22	47	15	70.1	47.9
5. PL + PR + PT(3)	229*	22	20	15	87.5	46.4
6. PL + PA(2)	63	26	110	15	15.9	36.4
6. PL + PR(2)	65	11	109	20	16.7	15.7
7. PL + PT(2)	93	26	100	15	23.5	37.9
8. PA + PR(2)	142	31	82	13	37.5	44.3
9. PA + PT(2)	87	23	102	16	22.1	32.9
10. PR + PT(2)	276*	28	39	14	70.1	40.0
11. PL(1)	110	7	97	19	14.0	5.0
12. PA(1)	13	44	110	14	1.7	31.4
13. PR(1)	22	15	109	18	2.8	10.7
14. PT(1)	67	45	103	14	8.5	32.1

The correlation between DEN and VAR was significant and positive for provenances of P. caribaea but was not significant for provenances of P. oocarpa and P. patula ssp. tecunumanii. Kanowski (1986) found the phenotypic correlation between DEN and VAR in a P. caribaea progeny test to be 0.65 at age ten years. It is possible that the genetic and environmental factors affecting DEN in P. caribaea also affect the numeric value of VAR in a similar manner.

Table 3.9 Correlation coefficients (r) of geographic and climatic parameters of experimental site and provenance origin on plot means of DEN and VAR of P. caribaea (df=620), P. oocarpa and P. patula ssp. tecunumanii (df=196).

Trait	<u>P. caribaea</u>		<u>P. oocarpa</u> and <u>P. patula</u> ssp. <u>tecunumanii</u>	
	DEN	VAR	DEN	VAR
VAR	0.701*		0.489	
Site latitude	-0.206	-0.568	0.197	0.896**
Site altitude	-0.872**	-0.751**	0.212	-0.568
Site rainfall	0.451	0.044	-0.518	-0.138
Site temperature	0.716*	0.795**	-0.505	0.194
Site age	-0.028	0.600	0.242	0.153
Provenance latitude	0.328	0.362	-0.374	-0.217
Provenance altitude	0.421	0.833**	-0.131	-0.562
Provenance rainfall	-0.436	-0.748*	-0.168	0.324
Provenance temperature	-0.417	-0.863**	0.292	0.563

Conclusion

The regression equations using site and provenance parameters combined with the correlations of these traits with DEN and VAR give an idea of the relative importance of climatic and geographic parameters. For DEN of P. caribaea, the significant and negative correlation with site altitude and the fact that this parameter accounted for more of the total sum of squares than any other single parameters support previous findings (Barnes et al., 1977). It can thus be said with some certainty that the wood density of P. caribaea will be lower at higher altitude though the data here was insufficient to develop predictive equations. This lower wood density would partly be caused by the lower temperature and rainfall at these higher altitudes and would explain why DEN was positively and significantly correlated with site temperature ($r=0.716$). The correlations of VAR with site parameters followed the same pattern as DEN in P. caribaea. Planting areas at low altitude

with higher mean annual temperatures should result in trees of P. caribaea with higher mean DEN and VAR.

The low per cent sum of squares accounted for by provenance effects for DEN of P. caribaea was surprising. For VAR of this species, the negative and significant correlations with provenance rainfall and temperature indicate that the forest manager can decrease VAR by planting seed collected from provenances at low altitudes such as the Guanaja provenance. The analyses performed here would suggest that for P. caribaea, VAR is under more genetic control than DEN.

The only significant correlation in P. oocarpa and P. patula ssp. tecunumanii was between VAR and site latitude. Site latitude would affect the intensity and duration of light. The higher VAR in these species when planted at higher latitudes would suggest that changes in day length and/or light intensity result in an increase in the width and frequency of high density wood (see Chapter 2.4). Richardson (1964) found that conifer seedlings had increased cell wall thickness when grown under increasing light intensity. This increased cell wall thickness could result in an increase in the width and frequency of high density wood but Brown (1970) has cautioned that "there is no evidence that day length per se is involved in latewood formation in conifers under natural conditions". The data presented here are insufficient for conclusions to be drawn concerning the effect of site latitude on VAR of P. oocarpa and P. patula ssp. tecunumanii. Very few forest managers have the opportunity to vary by more than a few degrees the latitude at which plantations of this species could be established. The observation of low VAR at low latitude may indicate a photoperiod effect but, more importantly, low VAR has been observed to affect certain papermaking traits. The correlation of VAR with pulp and paper-making traits (Chapter 5) indicates the importance of this trait.

4. ASSESSMENT OF PULP AND PAPER-MAKING TRAITS

While numerous forestry organizations in the world are selecting and breeding for improved wood properties, very few are actually selecting and breeding for end product properties. In certain instances, wood properties are highly correlated with end products and selection for the former should lead to improvements in the latter (see, for example, Chapter 1.2). In Pinus taeda, however, high wood density resulted in pulps with inferior breaking length and burst factor (Barefoot et al., 1972). Burley and Palmer (1979) found in P. caribaea that burst index and tensile index were negatively correlated with mean densitometric density. Thus selection for increased wood density may result in inferior grades of paper and a more sensitive form of evaluation for paper-making ability than wood density has been needed for quite some time.

Evaluation of large wood samples (1.0 kg) is regularly undertaken at most pulp and paper plants throughout the world. This destructive sampling is acceptable for evaluating a species and there are numerous reports in the literature concerning variation between species with regard to pulp and paper-making traits (Palmer, 1985). These methods are unacceptable for sampling individual trees since obtaining a 1.0kg wood sample would necessitate the felling of the tree with a subsequent loss of its genetic potential. Vegetative material could be taken for grafting or storage but this then involves the expensive maintenance of large numbers of samples of which only a small proportion will be found to have acceptable paper-making traits.

One method of evaluating the pulp and paper-making traits of an individual tree is through micropulping. This technique involves the removal of a small quantity of wood from the standing tree. The sample is then pulped and analyzed for chemical consumption and ease of pulping. Test sheets made from this pulp can then be tested for strength and quality factors. In a study on 10mm

increment cores removed at breast height from trees of P. taeda, van Buijtenen et al. (1961) concluded that there was no significant difference between selected and check trees for any of the pulp and handsheet properties evaluated. However, in a study on grafts of P. taeda, van Buijtenen et al. (1968) found that clones were significantly different for percent yield and zero-span tensile strength. The material for this study consisted of approximately 25g of dry wood per tree derived by extracting 11mm increment cores at breast height. More recent discussions of micropulping can be found in Manville and Hunt (1977) and in Janin (1981). However, none of these studies have correlated micropulping to full scale results.

Palmer (1986) at the Tropical Development and Research Institute (TDRI), London, found that micropulping of wood samples from P. patula were significantly and positively correlated with full-scale results for total yield, kappa number, apparent density, tensile index, stretch, tensile energy absorption index, tear index, burst index and fold when the pulps were beaten for the same length of time. Wood samples were derived from discs taken at equal intervals from the bole of the tree with a sample for micropulping of approximately 60g being taken from increment cores extracted at breast height. The sample size for this study was only nine trees but current work at TDRI on a larger number of P. caribaea and P. oocarpa samples has shown similar results. These significant correlations for micropulping and full-scale results indicate that samples removed at breast height give a good indication of the paper-making potential of the tree being sampled.

4.1 Correlation of full-scale pulping with micropulping

One industrial organization, Sappi, was interested in developing the micropulping technique into a method of tree evaluation. At their Enstra research centre, microdigesters of 800ml capacity were fabricated and following testing were ready to be used for

micropulping. It was first necessary to determine if full-scale results gave good correlation with micropulping. For this assessment, eighteen trees of similar age and growing conditions in the Eastern Transvaal, South Africa, were selected (Table 4.1). To be included in the assessment, trees had to be free of major defects such as forking and be growing under moderate competition from the surround trees. From each tree, five 12mm increment cores were taken at breast height for micropulping. The trees were then felled and a disc of 2.5cm thickness was removed at ten per cent height intervals to a top diameter of 8cm. This sample was assumed to represent the whole tree. The discs were debarked, chipped and allowed to dry in the sun for three days. From this whole tree sample, a 1.0kg sample was drawn for the normal full scale pulp evaluation used by Sappi. A second sub-sample of 100g from the whole tree sample, was drawn for micropulping. Each tree was therefore represented by two samples for micropulping and one for full-scale pulping.

A kraft cook was used and the cooking conditions are listed in Table 4.2. The pulp was beaten at 15,000 revolutions in a lampen beater. Hand sheets were made using the Frank Sheet Machine and were conditioned to constant temperature and humidity prior to sheet testing. A detailed description of the assessment procedures for the pulp and paper-making traits can be found in Appendix 4.

There was insufficient pulp from certain of the increment core samples to provide 20g of pulp to be beaten in the Lampen beater and no correlation could be drawn between full-scale pulping and micropulping of increment cores. The 100g sub-sample taken from the whole tree sample was micropulped for fifteen of the trees, three of the original eighteen trees having been misplaced. The correlation of full-scale pulping and micropulping of this sub-sample are presented in Table 4.3. A study to evaluate micropulping of increment cores with full scale results has been undertaken and will proceed once a beater capable of beating 10g

of pulp is in place at Enstra.

Table 4.1 Sample description for the correlation of traits from full-scale pulping and micropulping.

Tree No.	Species	Origin ¹	10% Height Interval (m)
1	<u>P. oocarpa</u>	Border row	1.8
2	<u>P. elliottii</u>	Border row	1.6
3	<u>P. elliottii</u>	Border row	1.4
4	<u>P. elliottii</u>	Border row	1.5
5	<u>P. patula</u> ssp. <u>tecunumanii</u>	Border row	1.8
6	<u>P. patula</u> ssp. <u>tecunumanii</u>	Border row	1.6
7	<u>P. patula</u> ssp. <u>tecunumanii</u>	Border row	1.7
8	<u>P. oocarpa</u>	Border row	1.6
9	<u>P. taeda</u>	Plantation	1.1
10	<u>P. taeda</u>	Plantation	1.1
11	<u>P. taeda</u>	Plantation	1.1
12	<u>P. patula</u>	Plantation	1.4
13	<u>P. patula</u>	Plantation	1.3
14	<u>P. patula</u>	Plantation	1.4
15	<u>P. caribaea</u>	Border row	1.6
16	<u>P. caribaea</u>	Border row	1.6
17	<u>P. caribaea</u>	Border row	1.4
18	<u>P. oocarpa</u>	Border row	1.5

¹All of the trees sampled had been pruned to 5.0m and were growing in stands or trials that had been thinned twice. The approximate age of these trees was twelve years. The border row trees were from provenance trials.

Table 4.2 Cooking conditions.

Maximum temperature °C	170
Time to 170°C (minutes)	110
Time at 170°C (minutes)	60
Liquor to oven dry wood ratio	5.4:1
Active alkali, as Na ₂ O % on oven dry wood	22

The correlations of full-scale pulping and micropulping results were positive and significant for the pulp yield and paper strength traits. These are the most important traits for Sappi as well as for numerous other organizations concerned with the

manufacture of kraft paper from pines. The correlations would indicate that micropulping of 100g of wood chips could be used to assess trees for their paper-making ability.

Table 4.3 Correlations of pulp and paper-making traits from full-scale (1.0kg) and micropulping (100g) samples of fifteen trees of Pinus sp. in the Eastern Transvaal, South Africa.

Trait	Correlation (r)	Significance
Kappa no.	0.323	ns
Screened yield (%)	0.753	p<0.01
Reject yield (%)	0.638	0.01<p<0.05
Total yield (%)	0.726	p<0.01
Spent liquor-AA	0.100	ns
Spent liquor-Na ₂ S	0.130	ns
% total solids	0.064	ns
C.S.F.	0.725	p<0.01
% stretch	0.496	0.05<p<0.10
Breaking length	0.548	0.05<p<0.10
Burst index	0.845	p<0.01
Tear index	0.677	p<0.01
Bulk specific	0.728	p<0.01
Porosity	0.751	p<0.01
T.E.A.	0.434	ns

4.2 Micropulping assessment of pine species/provenances in South Africa

Following the acceptable correlations between full-scale and micropulping for the pulp yield and paper strength traits, a study was undertaken to evaluate provenances of P. caribaea, P. oocarpa and P. patula ssp. tecunumanii growing in provenance trials in two different areas of South Africa. There has been an

interest in these species for afforestation due to their rapid volume growth but very little is known about their paper-making ability. The trials were established and maintained by the South African Forestry Research Institute with seed supplied by the Oxford Forestry Institute. These trials were discussed for provenance and species differences in DEN, VAR, VUB and DMI in Chapter 2. The provenances selected for micropulping were superior in terms of volume under bark to the P. elliottii controls and are listed in Table 4.4. In each block of each of the sampled provenances, two trees were sampled by removing two increment cores of 12mm diameter at breast height (1.3m). Where possible, the individual trees sampled were the same as those sampled by Gibson (1982). However, certain of the trees he sampled had been removed in subsequent thinnings and when this had occurred, the largest diameter tree(s) free of major defect was chosen. The gravimetric density of each increment core was determined and the ten trees were divided into five trees of "high" density and five trees of "low" density with the increment cores then being bulked according to gravimetric density. Each species/provenance was thus represented by two samples that will be referred to as classes.

The cooking conditions are listed in Table 4.2 and all other procedures were the same as in the initial study. The pulping and paper-making traits were analyzed using analysis of variance (ANOVA). Classes and provenances were considered to be fixed effects. Statistical differences between sites were not tested due to different provenance representation. The model used for both sites was:

$$X_{b_p} = \mu + B_b + P_p + E_{b_p}$$

where X_{b_p} is the value of the pulp and paper-making trait from the b^{th} class and the p^{th} provenance, μ is the population mean, B_b is the effect of the b^{th} class, P_p is the effect of the p^{th} provenance and E_{b_p} is the residual. The form of the ANOVA and the

expectation of mean squares are given in Table 4.5. The results of the ANOVA are summarized in Tables 4.6 and 4.7 for the Eastern Transvaal and Zululand, respectively. The correlations of the pulp and paper-making traits with gravimetric density are given in Table 4.8 for the two sites. The data for these analyses is presented in Appendix 5.

Table 4.4 Sample identification for micropulping.

Species	Provenance (abbreviation)	Location	Age (years)	VUB (dm ³)
<u>P. patula</u> ssp.	Camelias(CAM)	Wilgeboom	12.3	300
<u>tecunumanii</u>	Mountain Pine Ridge(MPRT)	Wilgeboom	12.3	264
<u>P. patula</u> ssp.	Rafael(RAF)	Wilgeboom	12.3	249
<u>tecunumanii</u>	Yucul(YUC)	Wilgeboom	12.3	288
<u>P. elliotii</u>	Seed orchard(PEL1)	Wilgeboom	12.3	69
<u>P. caribaea</u>	Alamicamba(ALA)	Mariti	11.2	99
<u>P. caribaea</u>	Byfield(BYF)	Mariti	11.2	126
<u>P. caribaea</u>	Guanaja(GUA)	Mariti	11.2	115
<u>P. caribaea</u>	Mountain Pine Ridge(MPRC)	Mariti	11.2	142
<u>P. caribaea</u>	Santa Clara(STA)	Mariti	11.2	119
<u>P. elliotii</u>	Seed orchard(PEL2)	Mariti	11.2	104
<u>P. oocarpa</u>	Cañas(CAN)	KwaMbonambi	12.0	151
<u>P. patula</u> ssp.	Camelias(CAM)	KwaMbonambi	12.0	143
<u>tecunumanii</u>	Mountain Pine Ridge(MPRT)	KwaMbonambi	12.0	126
<u>P. elliotii</u>	Commercial control(PEL)	KwaMbonambi	12.0	83
<u>P. caribaea</u>	Alamicamba(ALA)	KwaMbonambi	12.0	169
<u>P. caribaea</u>	Guanaja(GUA)	KwaMbonambi	12.0	202
<u>P. caribaea</u>	Melinda(MEL)	KwaMbonambi	12.0	123
<u>P. caribaea</u>	Mountain Pine Ridge(MPRT)	KwaMbonambi	12.0	204

In the Eastern Transvaal, the eleven pine species/provenances were significantly different ($p < 0.05$) for the following characteristics: reject yield(%), spent liquor(Na_2S), % total solids, wetness, C.S.F., burst index, bulk specific and porosity. In Zululand, the eight pine species/provenances were significantly different for the following traits: % total solids, % stretch, tear index and bulk specific.

Table 4.5 Analysis of variance and expectation of mean squares for pulp and paper-making traits.

Source	df	Expectation of mean squares
Provenances	p-1	$\sigma^2_e + b\sigma^2_p$
Classes	b-1	$\sigma^2_e + p\sigma^2_b$
Residual	(p-1)(b-1)	σ^2_e
Total	pb-1	

The ranked provenance means of VUB, total yield(%), tear index and burst index are presented in Figure 4.1 for the Eastern Transvaal and in Figure 4.2 for Zululand. These traits are very important for any manufacturer of kraft paper from pines and could be considered as selection criteria.

In the Eastern Transvaal, the two sources of P. elliotii were from the same seed orchard but were ranked very differently for tear index and burst index, and were ranked first and last for total pulp yield(%). Despite the low probability values for tear index and total pulp yield(%), it would seem likely that there is inherent variation in these traits within a species. The provenances of P. caribaea were ranked at the bottom for tear while provenances of P. patula ssp. tecunumanii were ranked above the trial mean for this trait. The provenances of P. patula ssp. tecunumanii were ranked near the bottom for burst index but values for this trait are generally acceptable for all of the species evaluated. High VUB and tear index would therefore suggest that provenances of P. patula ssp. tecunumanii rather than P. caribaea be considered for afforestation in areas similar to those of the Eastern Transvaal.

Table 4.6 Analysis of variance of micropulping results from the Eastern Transvaal, South Africa.

Trait	Source	df	MS(p value)
Kappa no.	Classes	1	86.01
	Spp./prov.	10	157.27 (p=0.052)
	Residual	10	53.60
Screened yield(%)	Classes	1	0.01
	Spp./prov.	10	12.14 (p=0.429)
	Residual	10	10.80
Reject yield(%)	Classes	1	0.58
	Spp./prov.	10	1.12 (p=0.032)
	Residual	10	0.32
Total yield(%)	Classes	1	0.73
	Spp./prov.	10	12.82 (p=0.411)
	Residual	10	11.08
Spent liquor (AA)	Classes	1	1.31
	Spp./prov.	10	0.63 (p=0.221)
	Residual	10	0.38
Spent liquor (NA)	Classes	1	0.02
	Spp./prov.	10	0.51 (p=0.004)
	Residual	10	0.29
% Total solids	Classes	1	0.001
	Spp./prov.	10	0.44 (p=0.042)
	Residual	10	0.14
Wetness	Classes	1	16.41
	Spp./prov.	10	21.13 (p=0.007)
	Residual	10	4.01
C.S.F.	Classes	1	2322
	Spp./prov.	10	5845 (p=0.007)
	Residual	10	1113
% Stretch	Classes	1	0.007
	Spp./prov.	10	0.16 (p=0.105)
	Residual	10	0.07
Breaking length	Classes	1	568010
	Spp./prov.	10	427065 (p=0.551)
	Residual	10	464405
Burst index	Classes	1	0.12
	Spp./prov.	10	0.51 (p=0.047)
	Residual	10	0.17
Tear index	Classes	1	5.70
	Spp./prov.	10	1.66 (p=0.208)
	Residual	10	0.97
Bulk specific	Classes	1	0.008
	Spp./prov.	10	0.008 (p=0.001)
	Residual	10	0.001
Porosity	Classes	1	599610
	Spp./prov.	10	13300446 (p<0.001)
	Residual	10	1168984
T.E.A.	Classes	1	2.7
	Spp./prov.	10	245.4 (p=0.288)
	Residual	10	170.6

Table 4.7 Analysis of variance of micropulping results from Zululand, South Africa.

Trait	Source	df	MS(p value)
Kappa no.	Classes	1	44.56
	Spp./prov.	7	40.88(p=0.694)
	Residual	7	60.94
Screened yield(%)	Classes	1	51.80
	Spp./prov.	7	9.63(p=0.312)
	Residual	7	6.55
Reject yield(%)	Classes	1	0.14
	Spp./prov.	7	1.75(p=0.564)
	Residual	7	1.98
Total yield(%)	Classes	1	57.34
	Spp./prov.	7	8.03(p=0.777)
	Residual	7	14.64
Spent liquor (AA)	Classes	1	2.71
	Spp./prov.	7	2.65(p=0.740)
	Residual	7	4.40
Spent liquor (NA)	Classes	1	1.83
	Spp./prov.	7	0.44(p=0.646)
	Residual	7	0.59
% Total solids	Classes	1	0.06
	Spp./prov.	7	0.88(p=0.032)
	Residual	7	0.19
Wetness	Classes	1	4.52
	Spp./prov.	7	9.05(p=0.053)
	Residual	7	2.44
C.S.F.	Classes	1	1351
	Spp./prov.	7	2695(p=0.110)
	Residual	7	1014
% Stretch	Classes	1	0.04
	Spp./prov.	7	0.15(p=0.020)
	Residual	7	0.03
Breaking length	Classes	1	65025
	Spp./prov.	7	614868(p=0.085)
	Residual	7	204268
Burst index	Classes	1	0.47
	Spp./prov.	7	0.16(p=0.260)
	Residual	7	0.10
Tear index	Classes	1	1.69
	Spp./prov.	7	1.73(p=0.006)
	Residual	7	0.20
Bulk specific	Classes	1	0.002
	Spp./prov.	7	0.005(p=0.007)
	Residual	7	0.001
Porosity	Classes	1	357604
	Spp./prov.	7	1009525(p=0.514)
	Residual	7	1023785
T.E.A.	Classes	1	91.2
	Spp./prov.	7	245.6(p=0.504)
	Residual	7	247.5

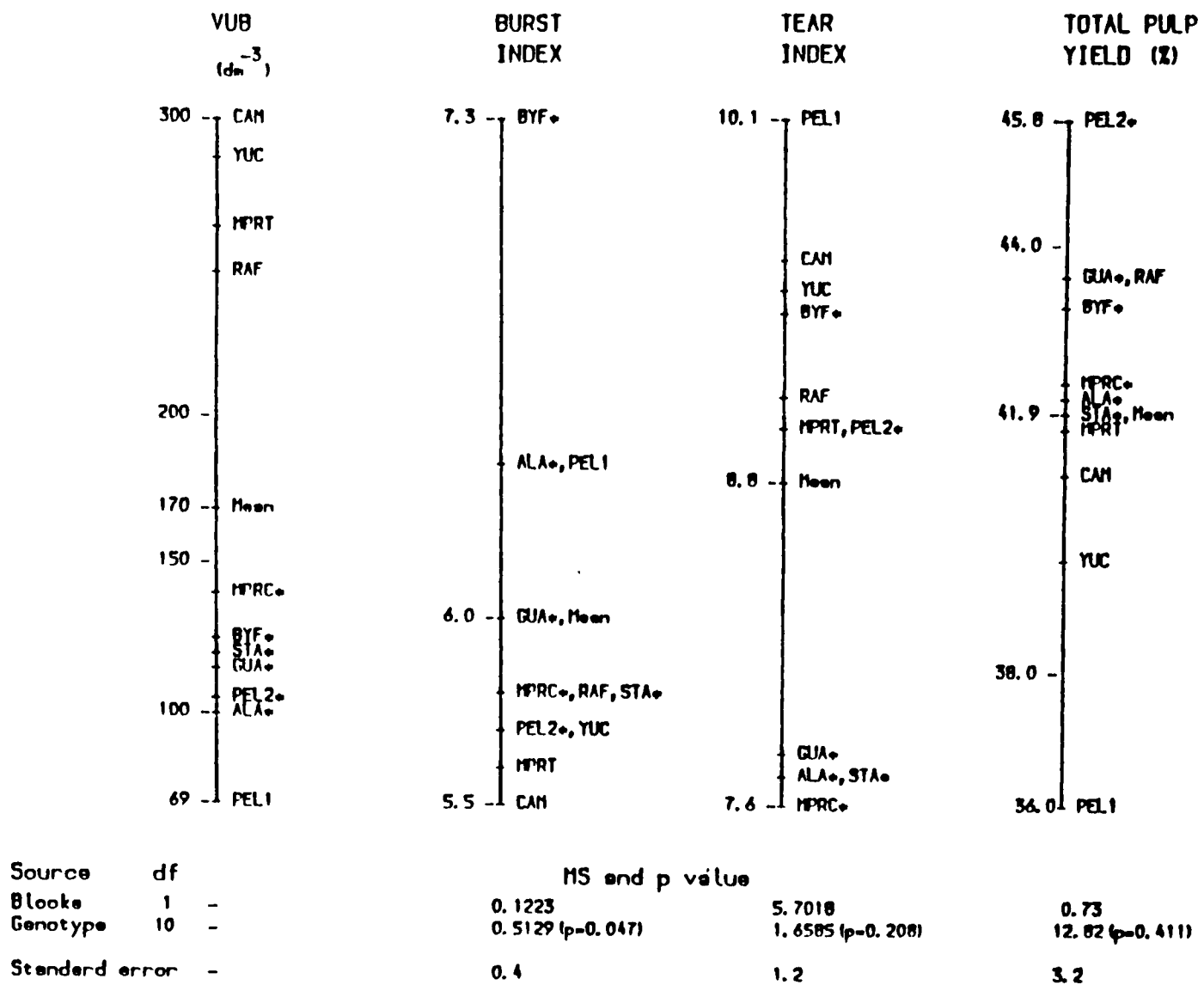


FIGURE 4.1 Analysis of variance and ranked means for VUB, burst index, tear index and total pulp yield (%) at Meriti (*) and Wilgeboom of eleven pine species/provenances in the Eastern Transvaal, South Africa.

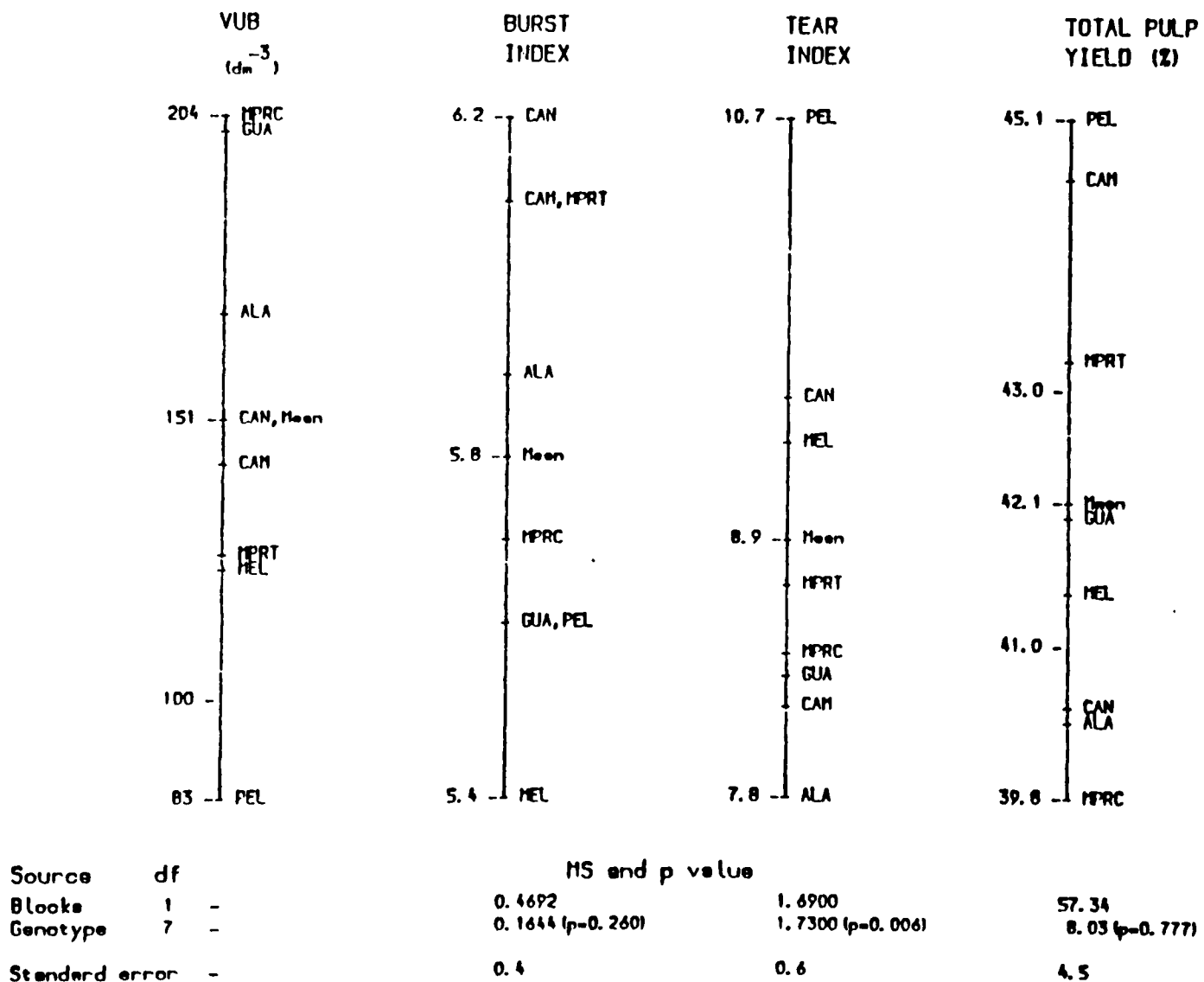


FIGURE 4.2 Analysis of variance and ranked means for VUB, burst index, tear index and total pulp yield (%) at KvaMbonambi of eight pine species/provenances in Zululand, South Africa.

In Zululand, the P. elliotii source was ranked last for VUB but was ranked first for tear index and total yield(%). The Cañas provenance of P. oocarpa had both high burst index and tear index but was low for total pulp yield(%). The volume superiority of the Cañas provenance relative to P. elliotii combined with its acceptable paper strength traits would indicate that P. oocarpa should be considered for afforestation in Zululand. Further evaluation of trees of P. oocarpa is currently underway at Sappi's Enstra research centre. The Guanaja and Mountain Pine Ridge provenances of P. caribaea had the highest VUB but were ranked below the trial means for burst index, tear index and total pulp yield(%). This gives support to the bias against this species by some paper-making organizations in South Africa.

Table 4.8 Correlation of pulp and paper-making traits of pine species/provenances in the Eastern Transvaal and Zululand with gravimetric density.

Trait	Eastern Transvaal Correlation coefficient (r)	KwaMbonambi Correlation coefficient (r)
Kappa no.	-0.030	-0.078
Screened yield(%)	-0.157	-0.670**
Reject yield(%)	0.035	0.111
Total yield(%)	-0.145	-0.547*
Spent liquor(AA)	-0.250	0.085
Spent liquor(NA)	0.120	0.464
% Total solids	-0.064	-0.011
Wetness	0.215	0.031
C.S.F.	-0.165	-0.030
% Stretch	-0.217	0.392
Breaking length	-0.264	-0.394
Burst index	0.006	-0.579*
Tear index	0.533*	0.503*
Bulk specific	0.465*	0.553*
Porosity	0.046	0.313
T.E.A.	-0.235	0.149

The results of micropulping generally confirm previously reported species differences. In Argentina, wood of P. oocarpa was found

to be superior to P. elliottii and P. taeda for burst and break but was inferior for tear index (Bucci et al., 1984). A detailed study in Brazil revealed that means of P. patula ssp. tecunumanii were superior to means of P. oocarpa by 12% in break, 9% in tensile and 10% in tear (Lima and Barrichelo, 1984). There was an insufficient number of P. oocarpa samples in this study to allow a proper comparison between the different species. However, these results should encourage further work with P. patula ssp. tecunumanii in southern Africa due to its superior volume production and acceptable paper-making traits.

The correlations of pulping and paper-making traits with gravimetric density were significant for tear index and bulk specific in the Eastern Transvaal and for screened yield(%), total yield(%), burst index, tear index and bulk specific in Zululand. A correlation of ± 0.7 is normally considered necessary before one would attempt to modify indirectly a trait by selection and breeding of a second trait. None of the correlations reported here were greater than ± 0.7 . However, correlations greater than ± 0.3 would suggest moderate improvements in the traits listed above by selecting for high or low density. Numerous researchers have also found gravimetric density to be significantly correlated with certain pulp and paper-making traits (Wangaard et al., 1966; Zobel et al., 1983) but correlation does not imply causation. Also, selection for high wood density may actually lead to a decrease in certain paper strength traits (Barefoot et al., 1972; Burley and Palmer, 1979).

Conclusion

The positive and significant correlations between full-scale and micropulping values for the pulp yield and paper strength traits indicate that small wood samples can be used to assess a tree's paper-making potential. The tree breeder can thus select for those papermaking traits that are in need of improvement as well

as for volume and form traits. Before one can establish a successful tree breeding programme for the papermaking traits, the heritability of the traits likely to be used in a selection index or independent culling system must be determined.

The fast growth and acceptable paper-making quality of P. patula ssp. tecunumanii provenances in the Eastern Transvaal and of the Cañas provenance of P. oocarpa is very encouraging. Superior phenotypes for volume and form will be sampled for micropulping assessment by removing increment cores of 12mm at breast height. The most important kraft paper-making traits for Sappi are tear index, burst factor and total pulp yield(%) and selection will at present centre on these traits as well as on volume and form.

The differences between significance levels and correlation coefficients of the provenances at the two sites indicate a possible need to develop separate breeding programmes for these areas. The financial benefits from pine plantations established using seedlings derived from superior phenotypes will certainly exceed the costs of such programmes. For example, an increase of one per cent in total pulp yield would result in a ten million Rand increase in sales for Sappi.

5. CORRELATION OF DENSITOMETRIC AND PAPER-MAKING TRAITS

The expense and complicated nature of pulp and paper-making evaluations necessitate the use of less costly methods to assess these traits. Gravimetric density is correlated with certain pulp and paper-making traits and is used by many organizations as a selection criterion (see Chapter 1.2). The correlation of gravimetric density with pulp and paper-making traits of pine species/provenances grown in South Africa is in Table 4.8 and indicates that these correlations are often insufficient for the development of selection indices. The use of densitometric mean density from twenty trees of P. caribaea grown in Fiji was found by Burley and Palmer (1979) to account for a large percentage of the variation in pulp and paper-making characteristics. Their study did not evaluate the correlation of VAR with pulp and paper-making traits. Ong (1978) also observed that DEN of P. caribaea accounted for more of the variation in pulp properties than any other wood property.

The fifteen trees involved in the correlation of full scale and micropulping (Chapter 4.1) were sampled for densitometric analysis by removing an 8mm increment core from breast height. The DEN and VAR of these fifteen trees were then correlated with micropulping results from the same trees. The correlation coefficients (r) are presented in Table 5.1.

The traits of breaking length and burst index were significantly and negatively correlated with DEN while bulk specific and porosity were significantly and positively correlated with DEN. The correlations with VAR were significant and negative for C.S.F. and porosity and significant and positive for spent liquor(AA) and tear index. In terms of the paper strength traits, selection for low DEN would result in improved breaking length and burst index while selection for high VAR would lead to

improved tear factor. The negative correlations of DEN with breaking length and burst index were also observed by Burley and Palmer (1979). Ong (1978) found trees of P. caribaea with high DEN were superior for tear index to trees with low DEN.

Table 5.1 Correlation of pulp and paper-making traits with DEN and VAR from fifteen trees of Pinus sp. in the Eastern Transvaal, South Africa.

Trait	Correlation coefficient (r)	
	DEN	VAR
Kappa no.	0.367	-0.317
Screened yield(%)	0.159	0.070
Reject yield(%)	0.039	-0.308
Total yield(%)	0.164	-0.011
Spent liquor(AA)	-0.135	0.539*
Spent liquor(Na ₂ S)	0.357	0.373
% Total solids	0.215	-0.014
C.S.F.	0.063	-0.513*
% Stretch	0.485	0.413
Breaking length	-0.641**	-0.053
Burst index	-0.601*	-0.037
Tear index	0.043	0.778**
Bulk specific	0.473*	0.051
Porosity	0.489*	-0.470*
T.E.A.	-0.208	0.153

There were significant ($p < 0.05$) and negative correlations of DEN with breaking length and burst index while the correlations of DEN with bulk specific and porosity were significant ($p < 0.05$) and positive. The correlation of VAR with spent liquor(AA) and tear index were significant ($p < 0.05$) and positive. In contrast, the correlation of VAR with C.S.F. and porosity was significant

($p < 0.05$) and negative.

It is felt by some paper-makers that a high percentage of latewood or wood of higher density results in papers with low burst index. The low DEN of the Canas provenance of P. oocarpa and of the Camelias and Mountain Pine Ridge provenances of P. patula ssp. tecunumanii at KwamBonambi (Figure 2.20) could be a determining factor in the high burst index of these provenances in the micropulping assessment (Figure 4.2).

The positive and significant correlation of VAR with tear index is interesting. The low VAR of the Alamicamba and Guanaja provenances of P. caribaea could therefore be one of the causes of the low tear index of these provenances in the micropulping assessment (Figures 4.1 and 4.2). High VAR seems to be due to the increased frequency of high density wood which would normally be caused by an increased percentage of cells with greater wall thickness. The contrast in wood of high VAR between fibers with thicker or more narrow cell walls could allow the latter to collapse forming a well bonded sheet. The thicker cell walled fibers could have a tendency to reduce the bonding in the sheet and hence increase tear factor.

While not being a paper-making trait of critical importance, the significant but different signs of the correlation of DEN and VAR with porosity indicate one of the difficulties in tree breeding. It might be difficult to improve porosity by selecting for DEN or VAR since these traits were themselves positively correlated in both series of trials. One exception to this correlation was the Guanaja provenance of P. caribaea which was consistently low for VAR and high for DEN. It is exceptions such as these that can often be desirable in any applied plant breeding programme.

Conclusion

The significant correlations between certain paper-making traits

and DEN were expected. It remains doubtful, however, as to whether the expense of densitometric analysis can be justified for large numbers of samples simply to obtain values of DEN alone when gravimetric density gives similar correlations at a fraction of the cost, time and effort.

The correlation between VAR and certain paper-making traits indicate that the densitometer might be used effectively to screen smaller numbers of wood samples. There are no reports in the literature of the effects of VAR on end use properties though reference is often made to range of density (maximum minus minimum) as a measure of wood variability. Variation in density is also often expressed in terms of density classes but the correlation of these with end use properties has never been reported. In fact, most authors have concluded that low wood variation is desirable (Wilcox and Smith, 1973; Olson and Arganbright, 1977; and Zobel et al., 1983). The conclusions reached by those and other authors with respect to wood variation have been based on supposition rather than data. The important paper strength trait of tear index would for example have been reduced if selection had been undertaken for wood of low VAR. The high tear index of paper made from trees of P. elliottii in Zululand, South Africa, would seem to confirm the positive correlation of this trait with VAR. Trees of this species were found to have values of VAR that were 57 to 74 percent higher than provenances of P. caribaea var. caribaea, P. caribaea var. hondurensis, P. oocarpa and P. patula ssp. tecunumanii (Figures 2.7 and 2.20). It should be stated that uniformity in terms of species, age, size and growing conditions of timber are desirable for most end products. Also, uniformity in wood density may be desirable for structural timbers or veneer. The results here, however, indicate that the tear factor of kraft paper will be improved by selection and/or the use of silvicultural practices that result in wood of decreased uniformity within a tree.

The correlations reported here would support the use of

densitometric analysis as a method of screening large numbers of wood samples to indicate potential end use properties. An organization must know the financial value of the traits that need to be improved as well as knowing the effect of selection for one trait on a second trait. For example, Barefoot et al. (1972) concluded that high wood density in P. taeda would lead to an increase in tear index and to a decrease in breaking length and burst factor. Selection and breeding for high wood density in P. taeda would thus certainly be unacceptable for many kraft paper grades. Burley and Palmer (1979) also reported that high density wood of P. caribaea yielded pulps with high tear index and low burst index and tensile index. For these reasons the final decision on an individual tree's papermaking properties must be based on the results of pulping evaluation although sample numbers could be greatly reduced by using densitometric analysis as a screening procedure.

6. CONCLUSIONS

The use of the densitometer to assess large numbers of wood samples can only be justified if the variables derived give a greater indication of end use properties than gravimetric density alone. The significant correlation of VAR with spent liquor(AA), C.S.F., tear index and porosity indicate that variables derived from the densitometer other than DEN can be used to indicate the potential of a genotype as a raw material for papermaking. The high VAR of the Poptun provenance of P. caribaea across sites suggests that further micropulping evaluation be undertaken with trees of this provenance. The low VAR of the Guanaja provenance of P. caribaea could discourage the use of this provenance as a raw material for kraft paper production. However, the volume superiority and high density of this provenance could be quite desirable for structural timber and for certain paper products such as tissue where high yield and wood uniformity are more important than inherent paper strength.

The comparison of P. caribaea, P. oocarpa and P. patula ssp. tecunumanii growing under similar conditions is urgently needed. The three locations used in this study to compare species and provenances were insufficient for firm conclusions to be made. Also, one of these locations was at high altitude where P. caribaea is known to have low DEN and possibly lower VUB than other pine species. Interest in P. patula ssp. tecunumanii could be greatly accelerated if this species could be shown to produce more VUB than P. caribaea at sites of low altitude. The superior VUB and acceptable papermaking properties of the P. patula ssp. tecunumanii provenances tested in South Africa indicate the potential of this species.

The correlations of DEN and VAR with experimental site and provenance origin characteristics could be very useful to forest managers and tree breeders. These correlations could indicate

superior provenances for DEN and VAR from which to make further collections. For certain organizations, the correlation of experimental site characteristics with DEN and VAR could be used to determine the best utilization of a specific site and genotype. The correlations calculated in this study were based on too few observations to be conclusive. Wood samples taken in trials with similar replication and sampling intensity could provide correlations of more practical use than those calculated here.

Much of the precision in the GEI analyses was lost due to differences in replication between and within sites. The Bartlett's Test revealed that the residual variances were significantly different in both series of trials and the degrees of freedom in the residual term were greatly reduced due to the use of plot means for DEN and VAR rather than values from individual radii. The lack of significant GEI for DEN and VAR in both species indicate that superior provenances for these traits will be ranked consistently when planted across sites. However, the values of provenances for DEN and VAR at a given site will very much depend on the rainfall, temperature and soil conditions at that site.

Despite the fact that no data was available to correlate micropulping of increment cores with full-scale pulping results, micropulping at Enstra of increment cores continues. The success of the micropulping technique of Palmer (1986) and the need of this type of phenotypic assessment should encourage other organizations to begin work in this neglected subject. The pine resource in South Africa must be increased with regard to both the quantity and quality of the fiber produced or serious shortages of this raw material will occur. The selection and breeding of pines for paper-making properties by Sappi will be undertaken using micropulping of increment cores as well as using volume and form traits.

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Appendix 1. Densitometric values plotted against distance from the pith for selected pine species/provenances at certain sites.

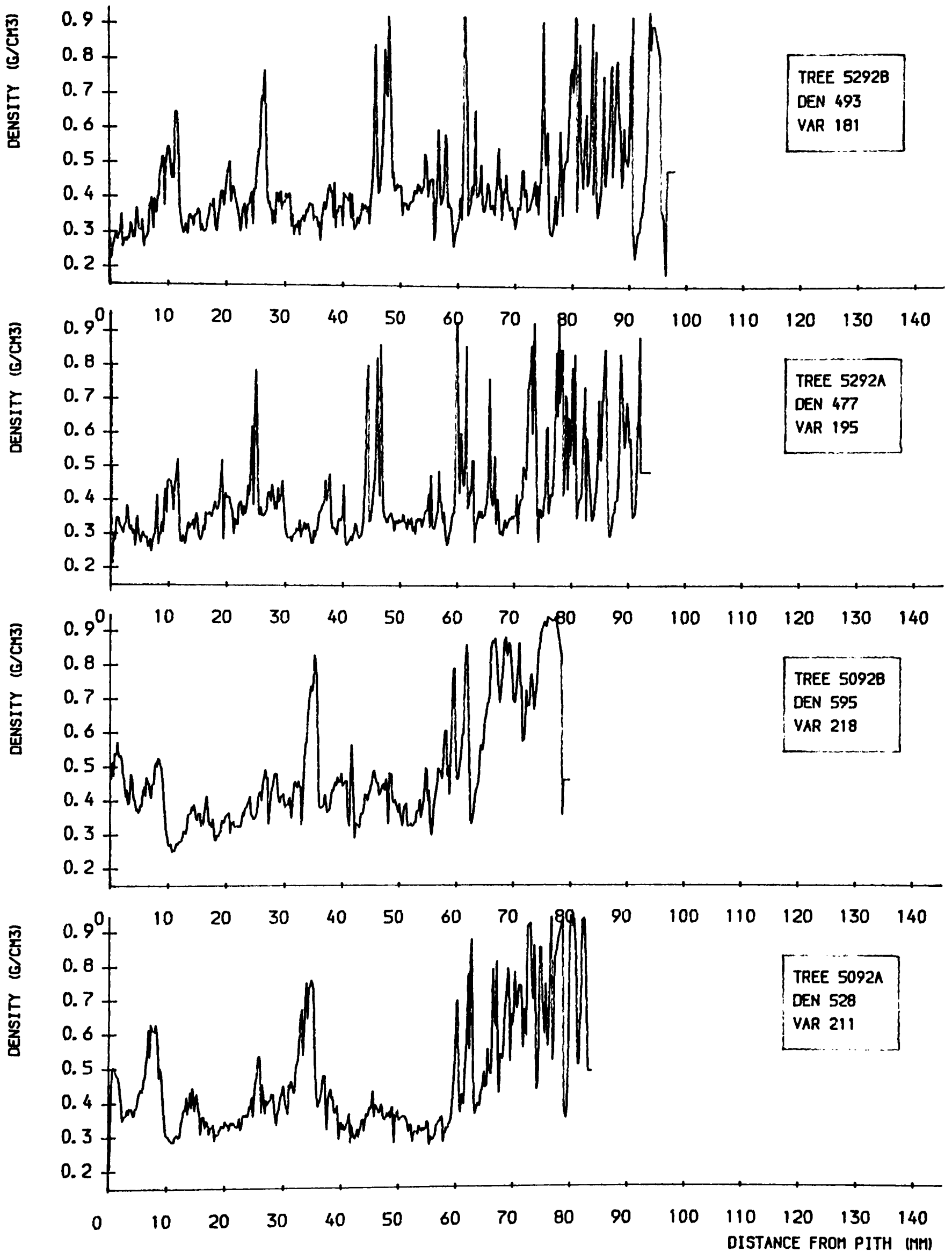


Figure 1.1 Wood density variation of two radii from each of two trees of the Alamcamba provenance of *P. caribaea* at the Ivory Coast.

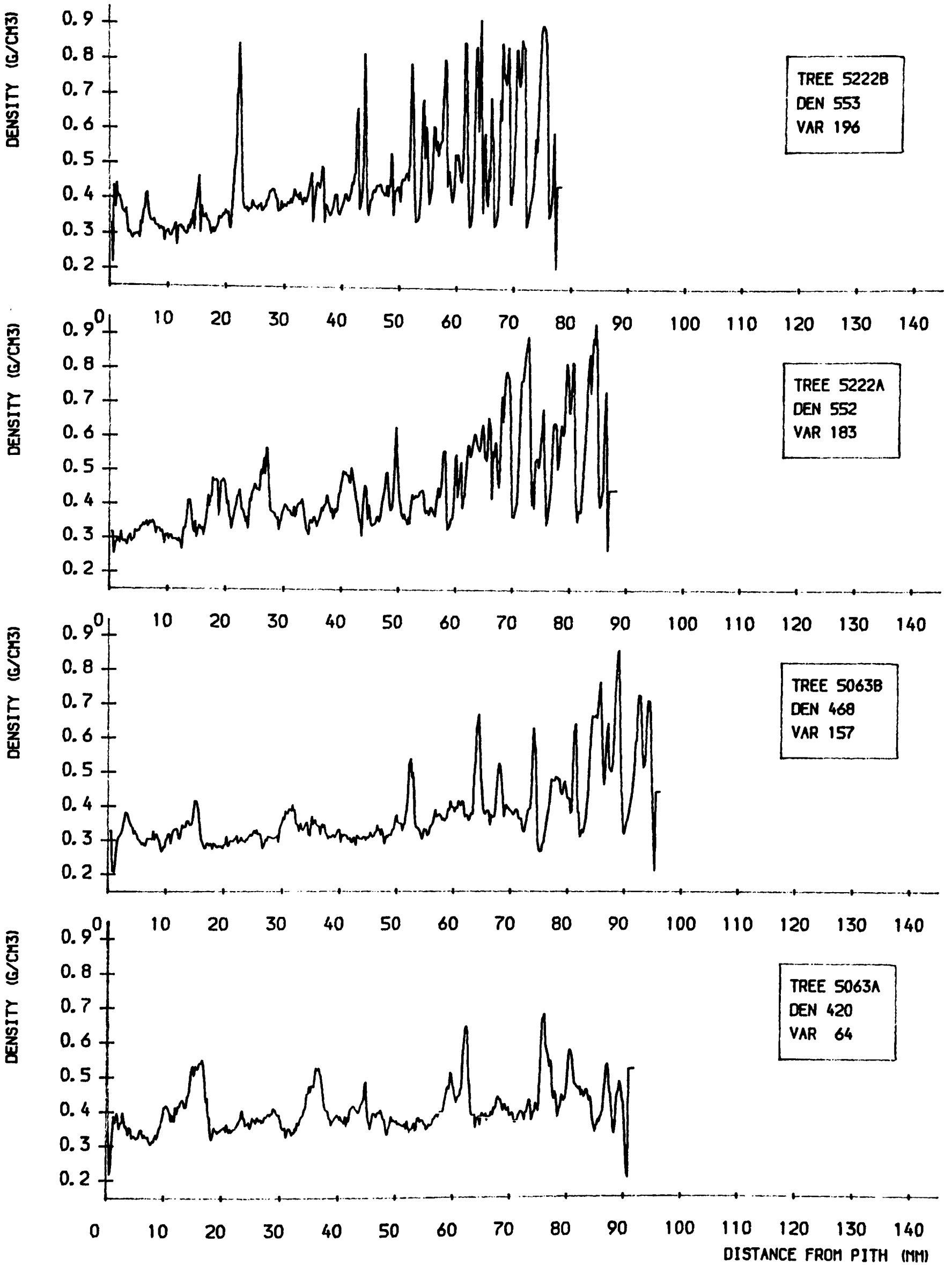


Figure 1.2 Wood density variation of two radii from each of two trees of the Guanaja provenance of *P. caribaea* at the Ivory Coast.

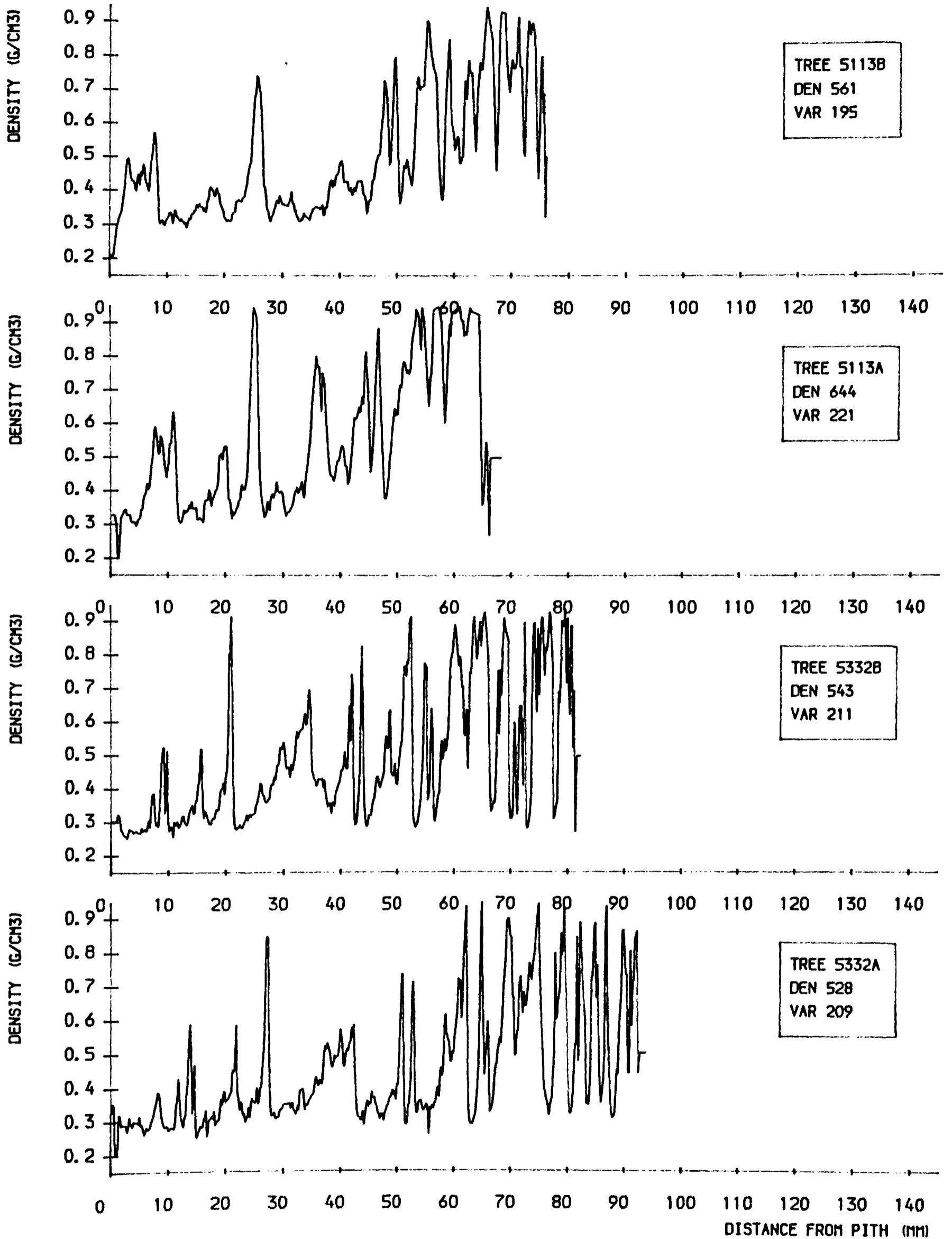


Figure 1.3 Wood density variation of two radii from each of two trees of the Mountain Pine Ridge provenance of *P. caribaea* at the Ivory Coast.

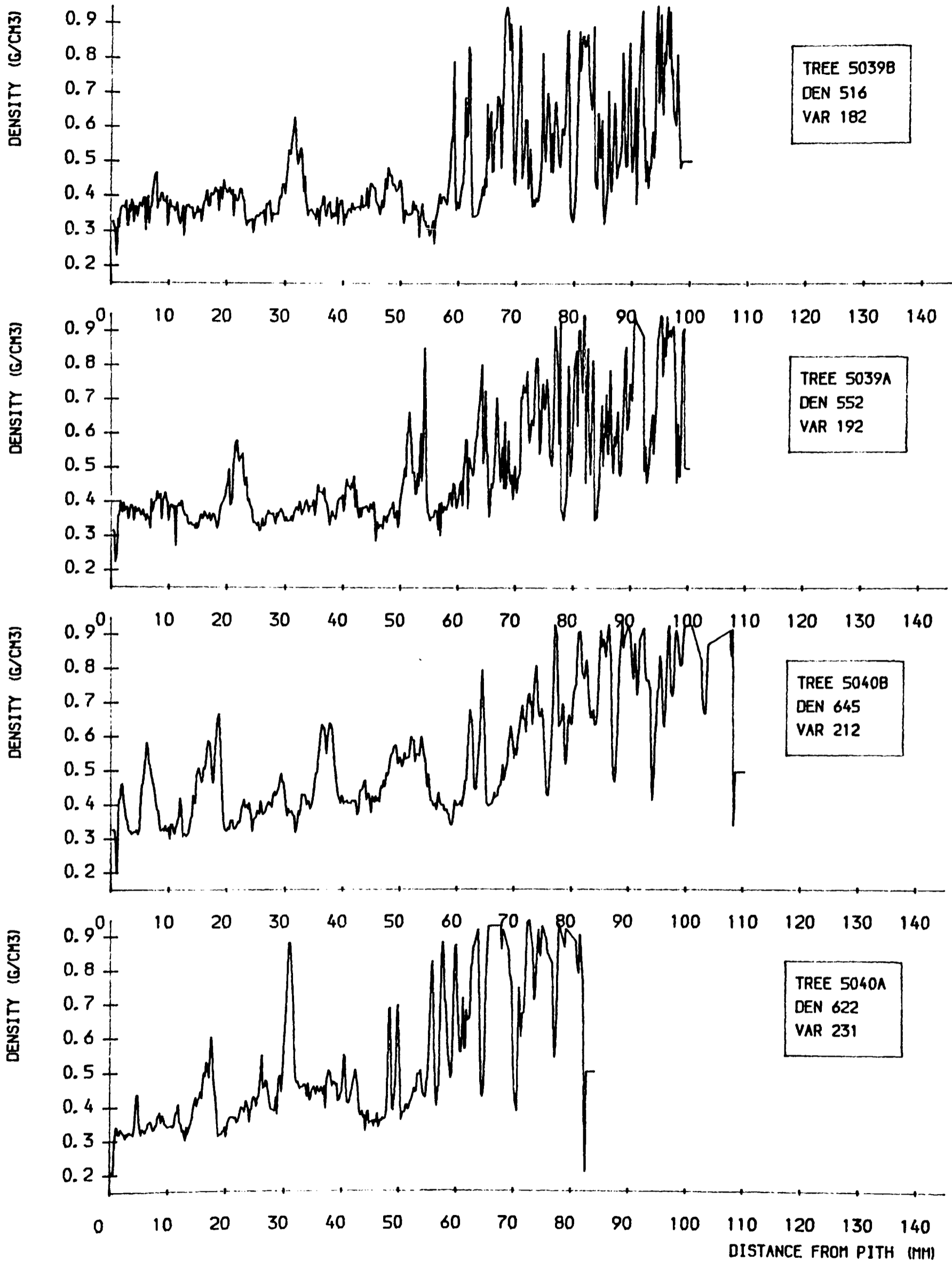


Figure 1.4 Wood density variation of two radii from each of two trees of the Poptun provenance of *P. caribaea* at the Ivory Coast.

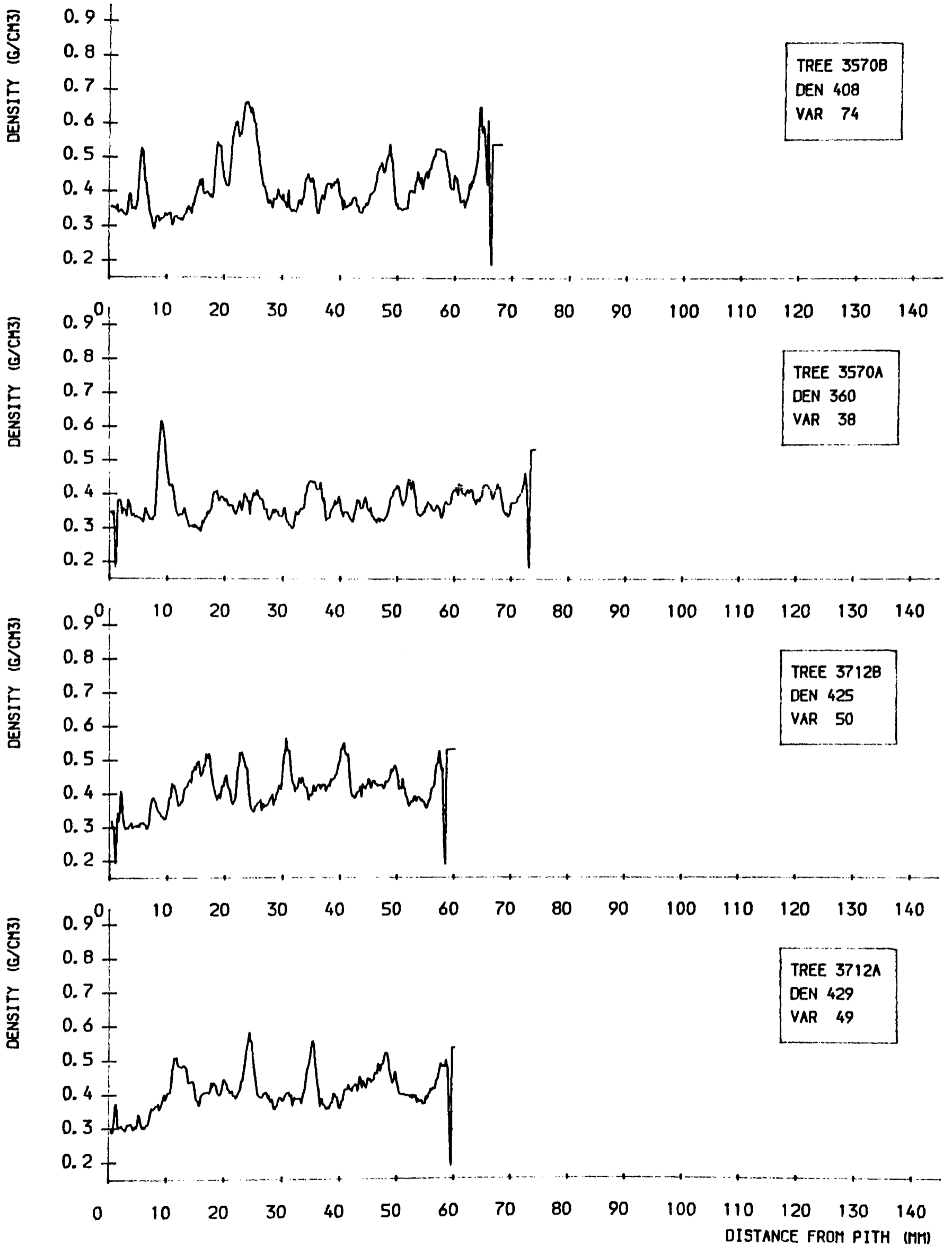


Figure 1.5 Wood density variation of two radii from each of two trees of the Alamcamba provenance of *P. caribaea* at Mariti.

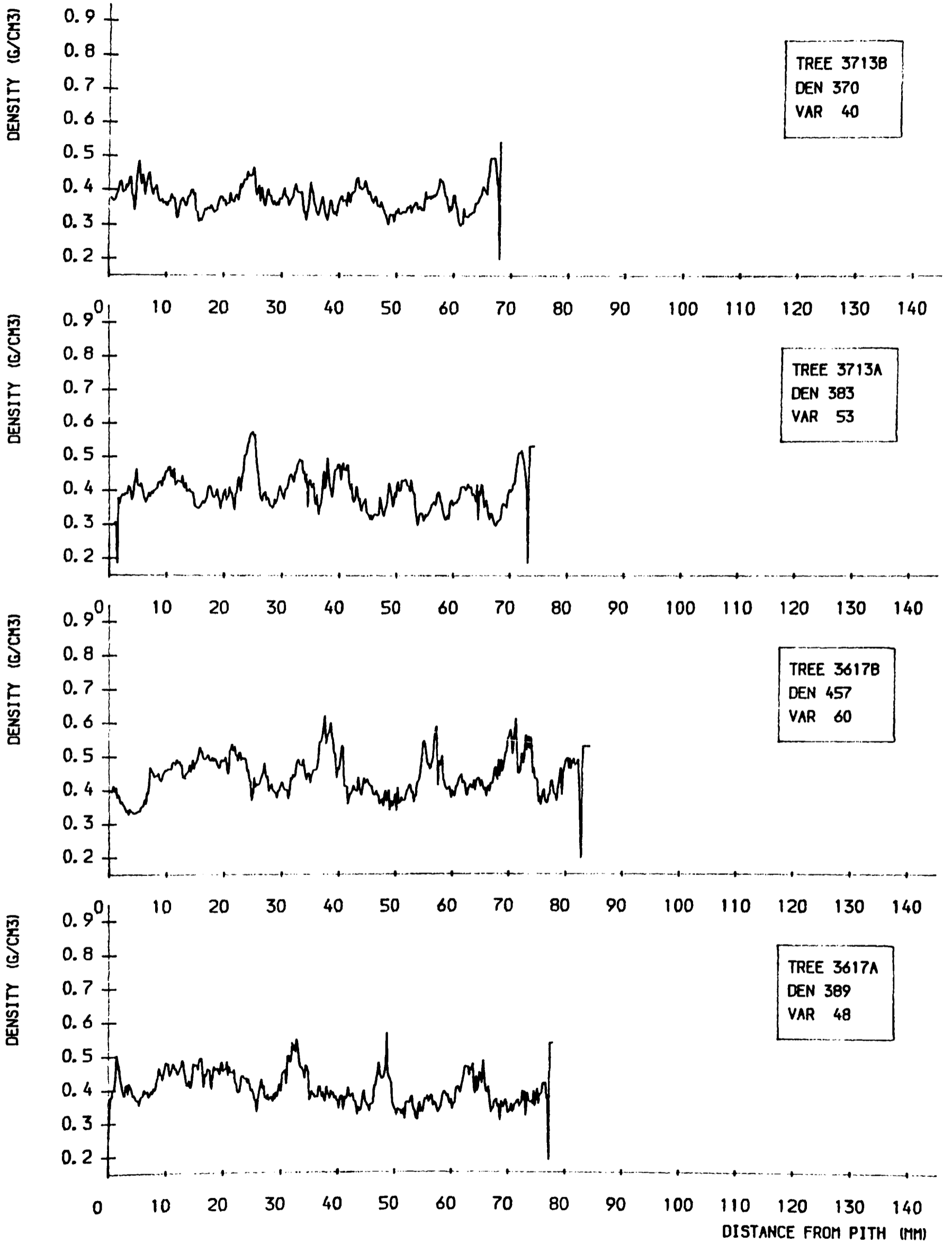


Figure 1.6 Wood density variation of two radII from each of two trees of the Guanaja provenance of *P. caribaea* at Mariti.

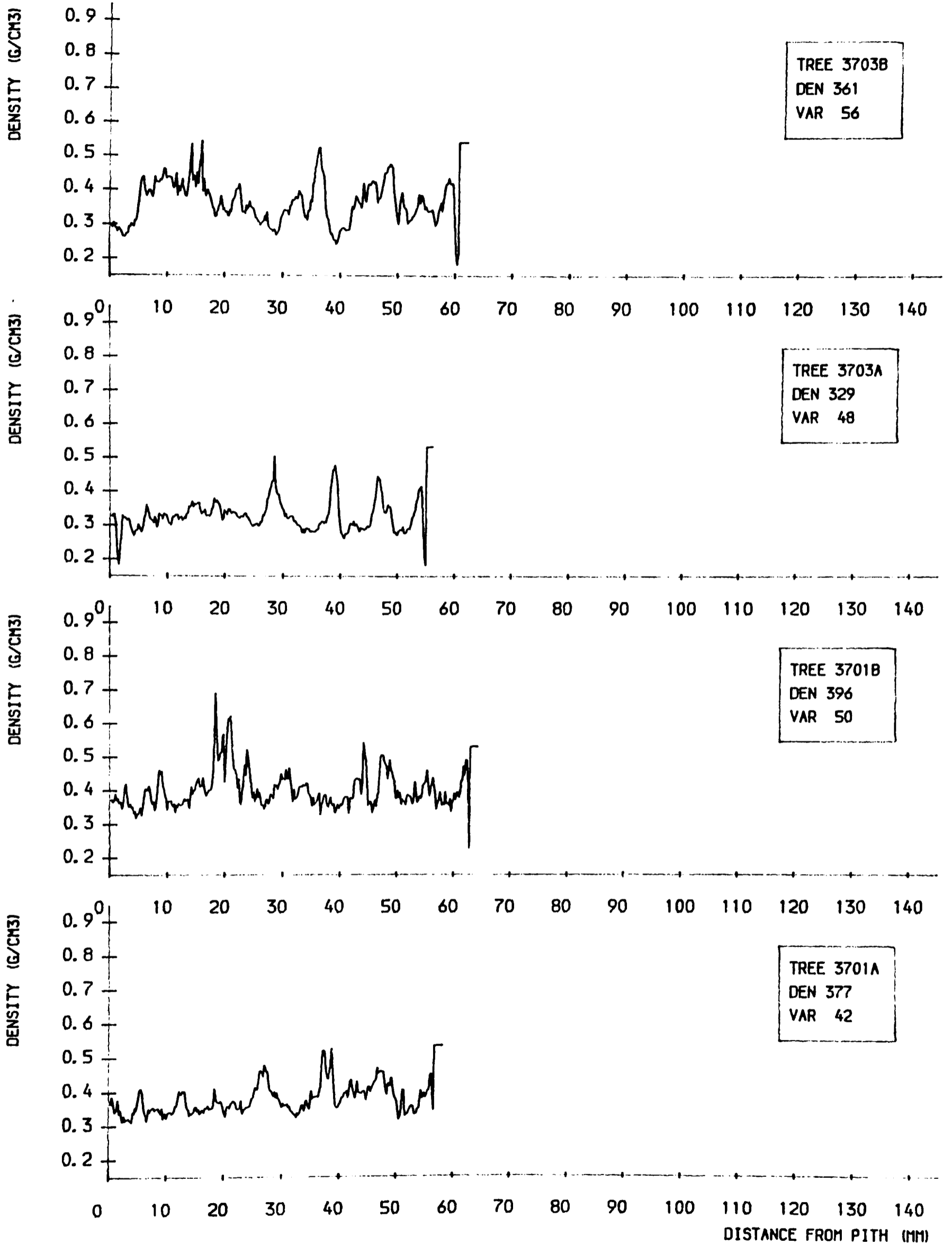


Figure 1.7 Wood density variation of two radii from each of two trees of the Mountain Pine Ridge provenance of *P. caribaea* at Mariti.

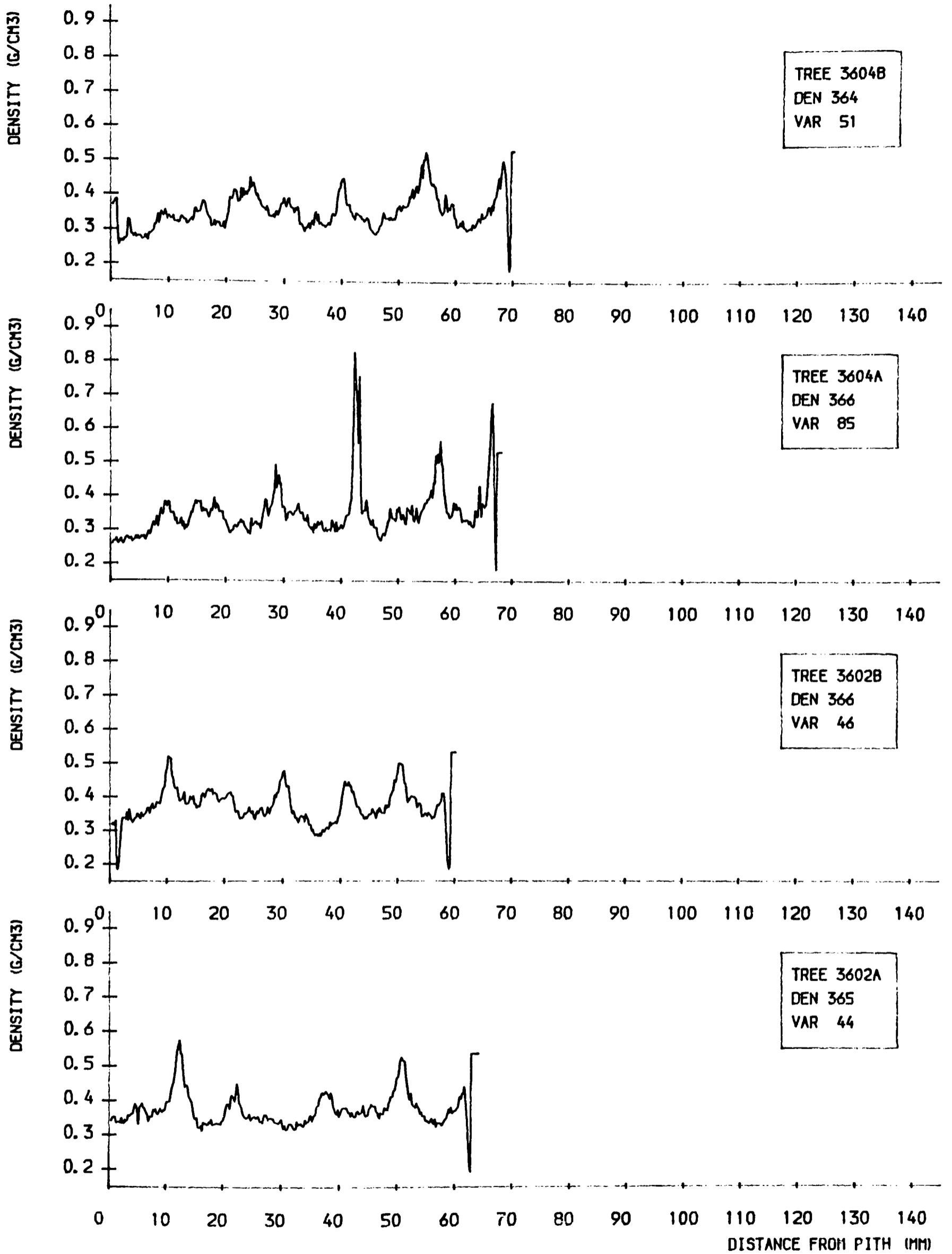


Figure 1.8 Wood density variation of two radii from each of two trees of the Poptun provenance of *P. caribaea* at Mariti.

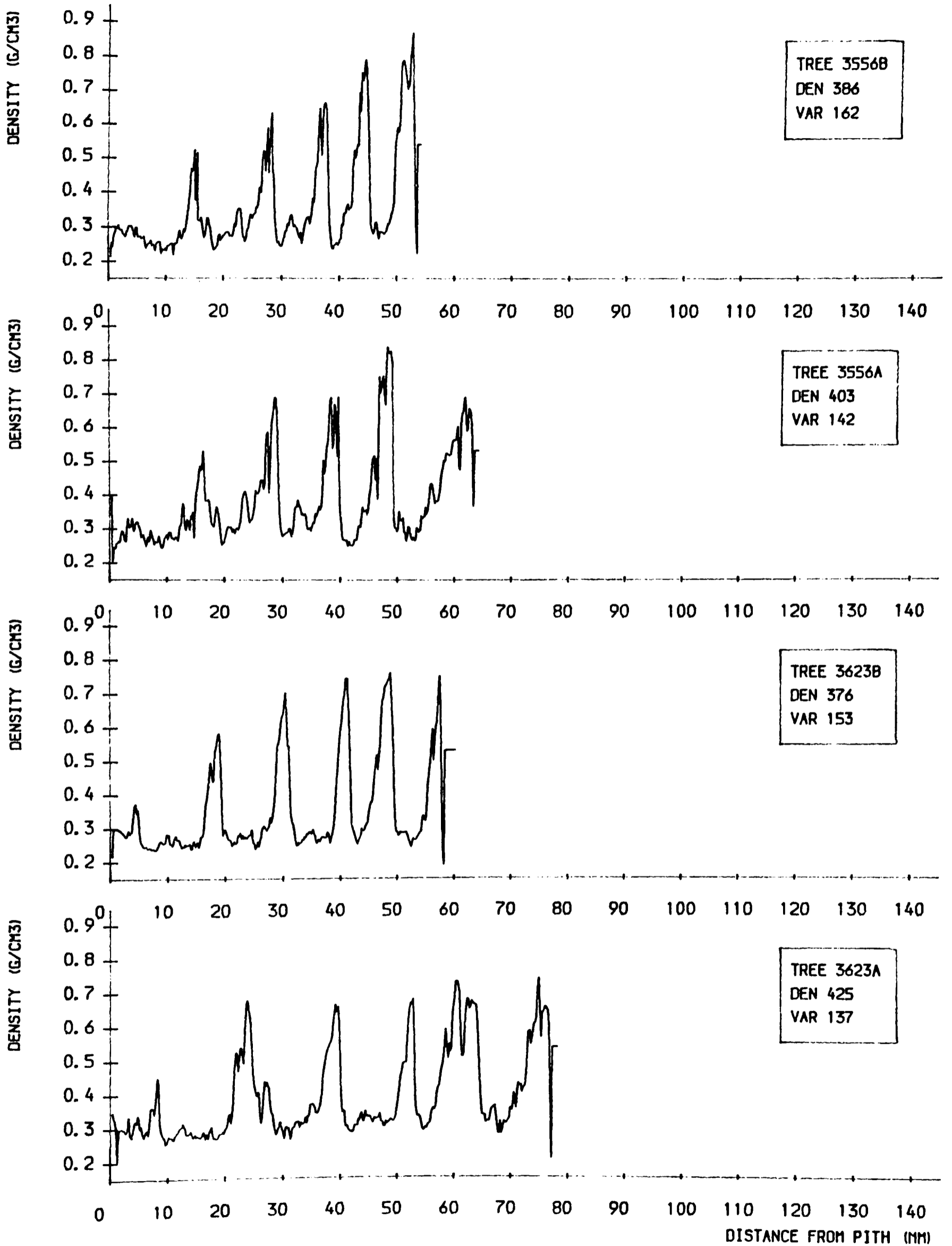


Figure 1.9 Wood density variation of two radii from each of two trees of *P. elliotii* at Mariti.

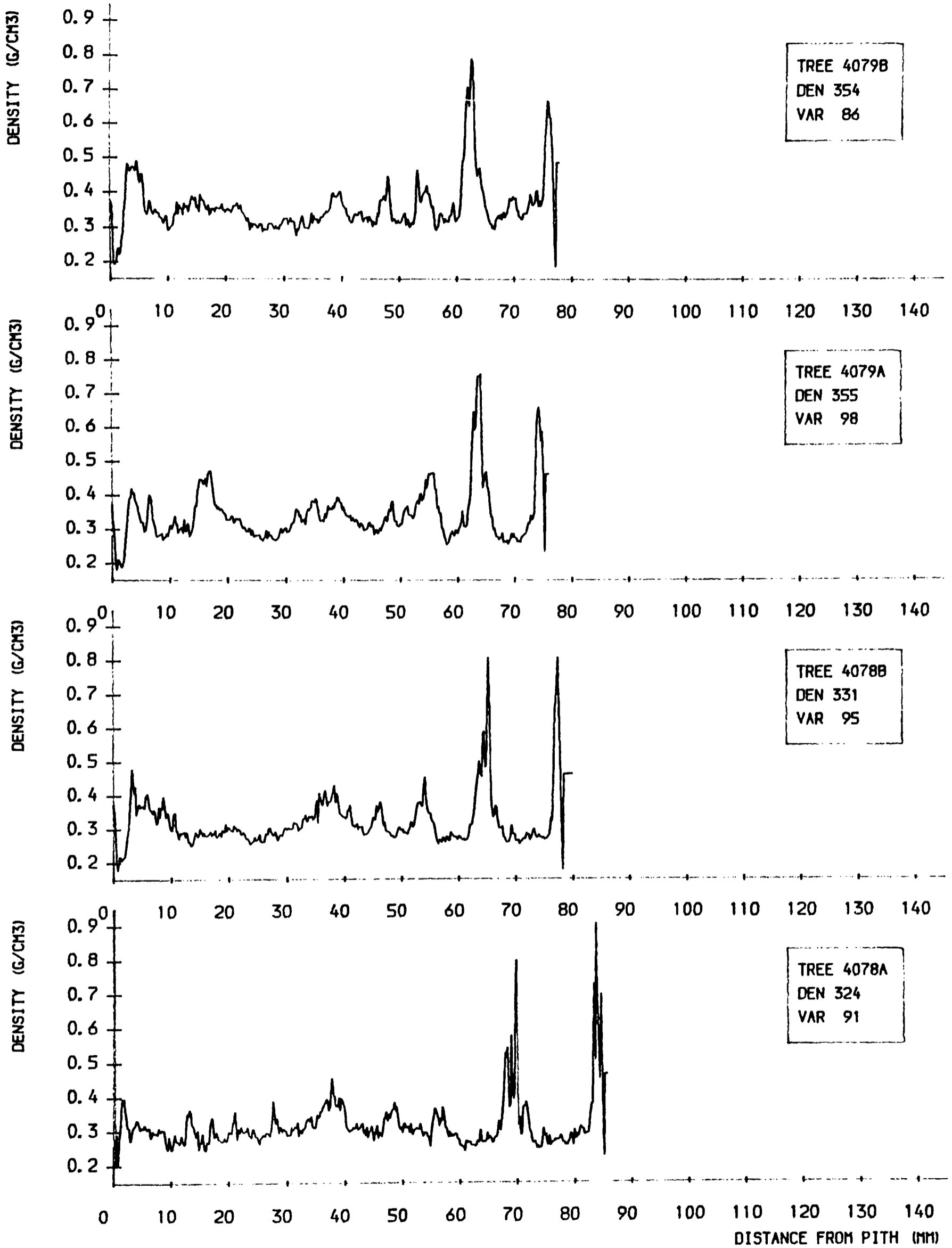


Figure 1.10 Wood density variation of two radii from each of two trees of the Alamicamba provenance of *P. caribaea* at Kwambonambi.

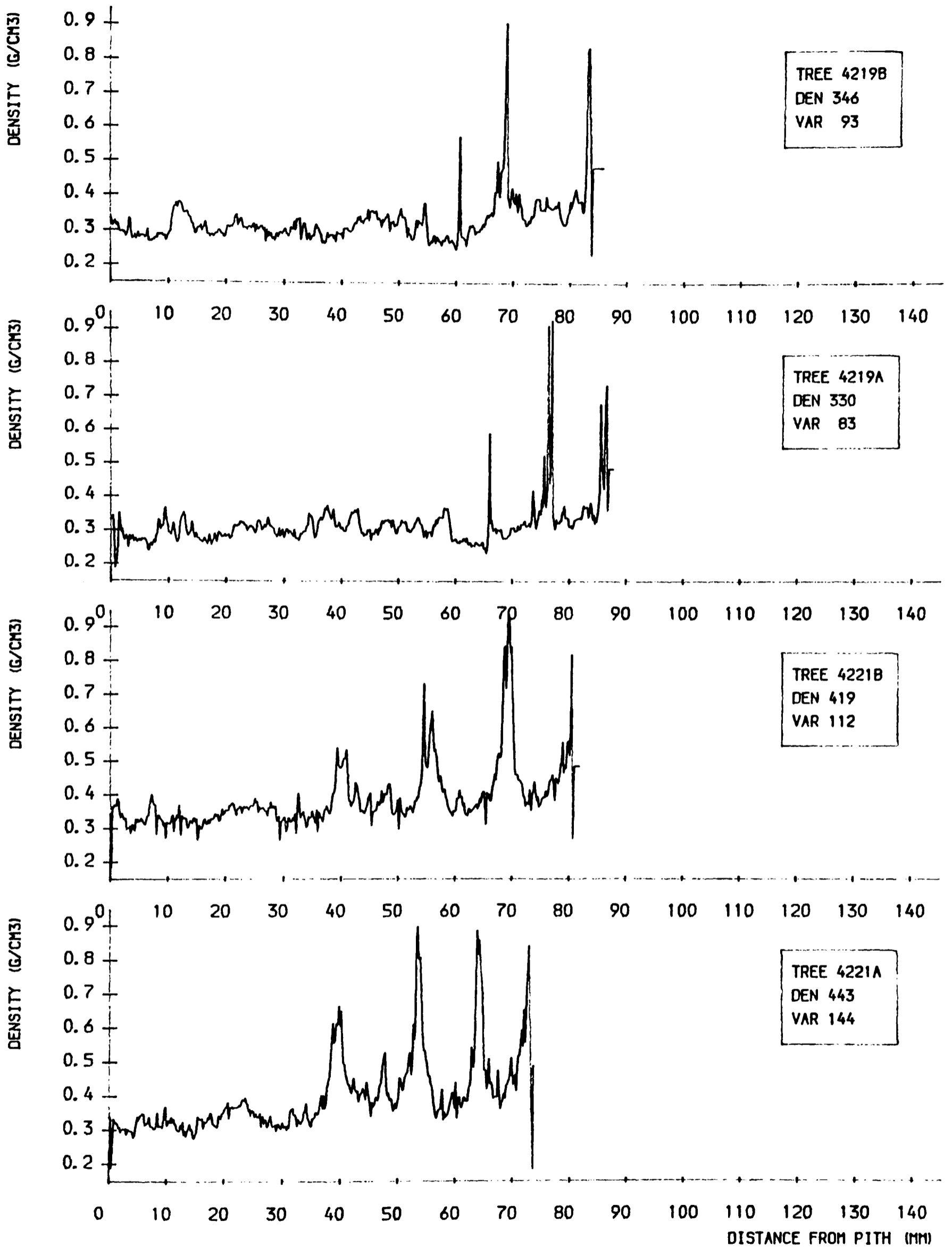


Figure 1.11 Wood density variation of two radii from each of two trees of the GuanaJa provenance of *P. caribaea* at KwaMbonambi.

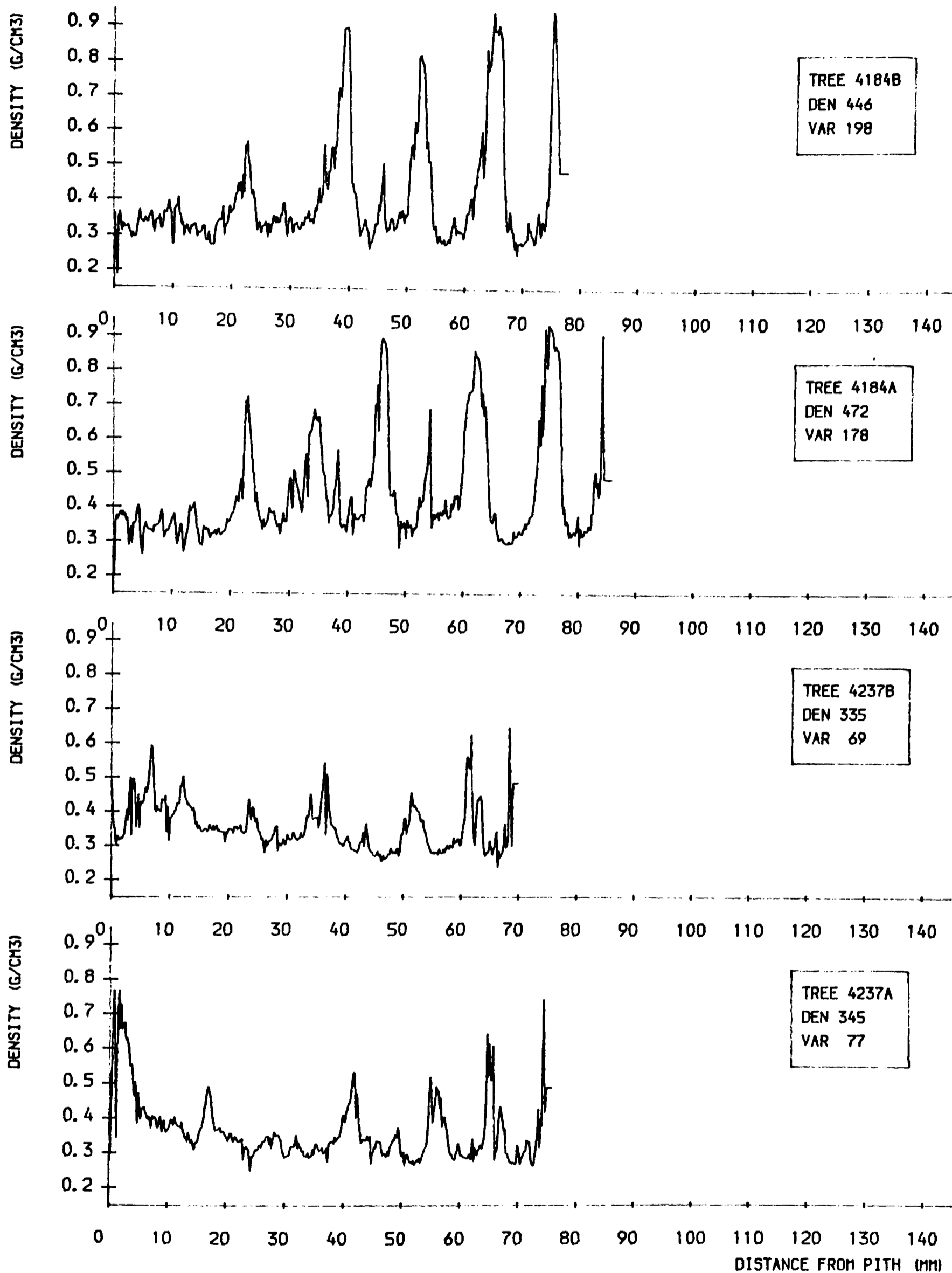


Figure 1.12 Wood density variation of two radii from each of two trees of the Poptun provenance of *P. caribaea* at Kwambonambi.

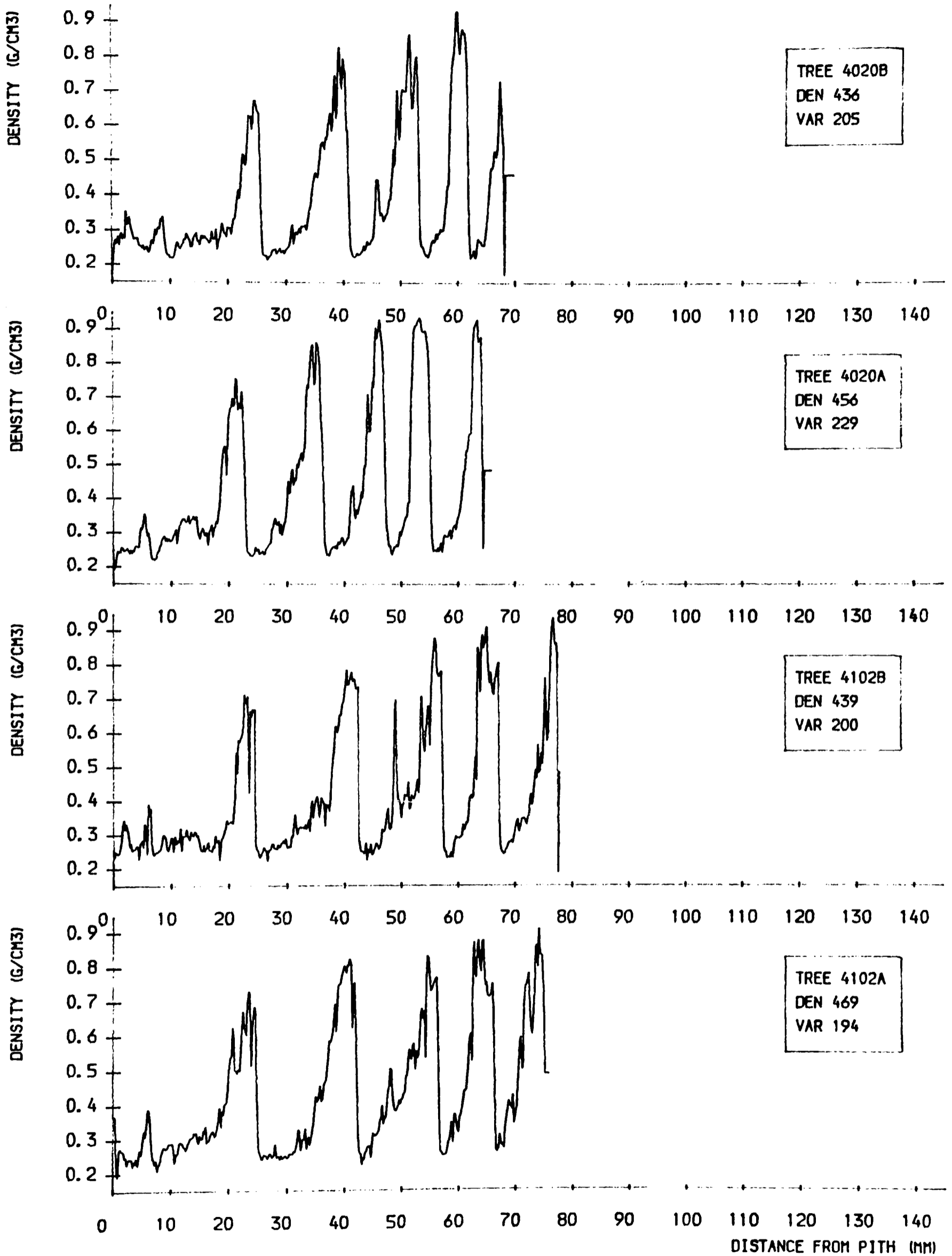


Figure 1.13 Wood density variation of two radii from each of two trees of P. elliotii at Kwambonambi.

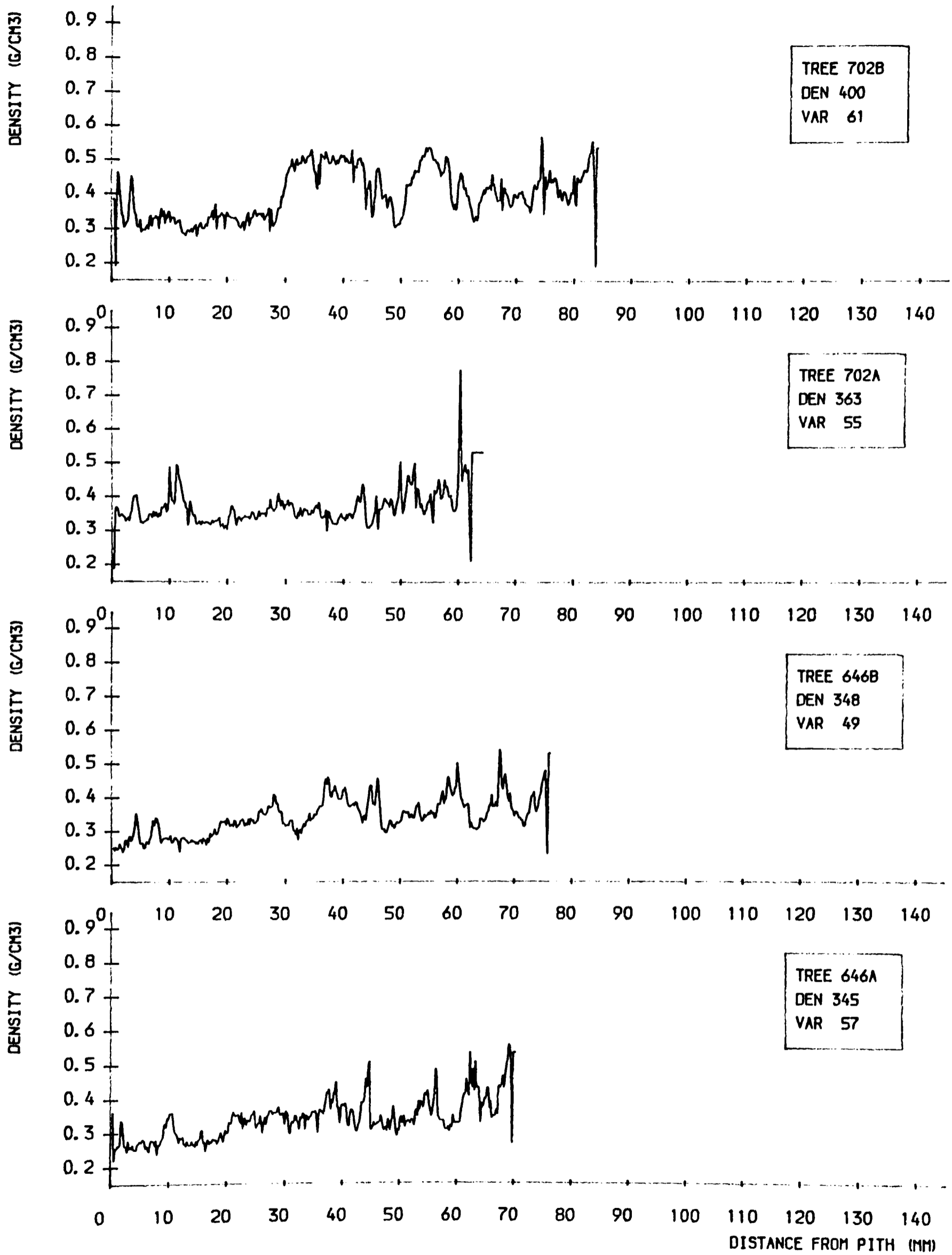


Figure 1.14 Wood density variation of two radii from each of two trees of the Alamcamba provenance of *P. caribaea* in Malaysia.

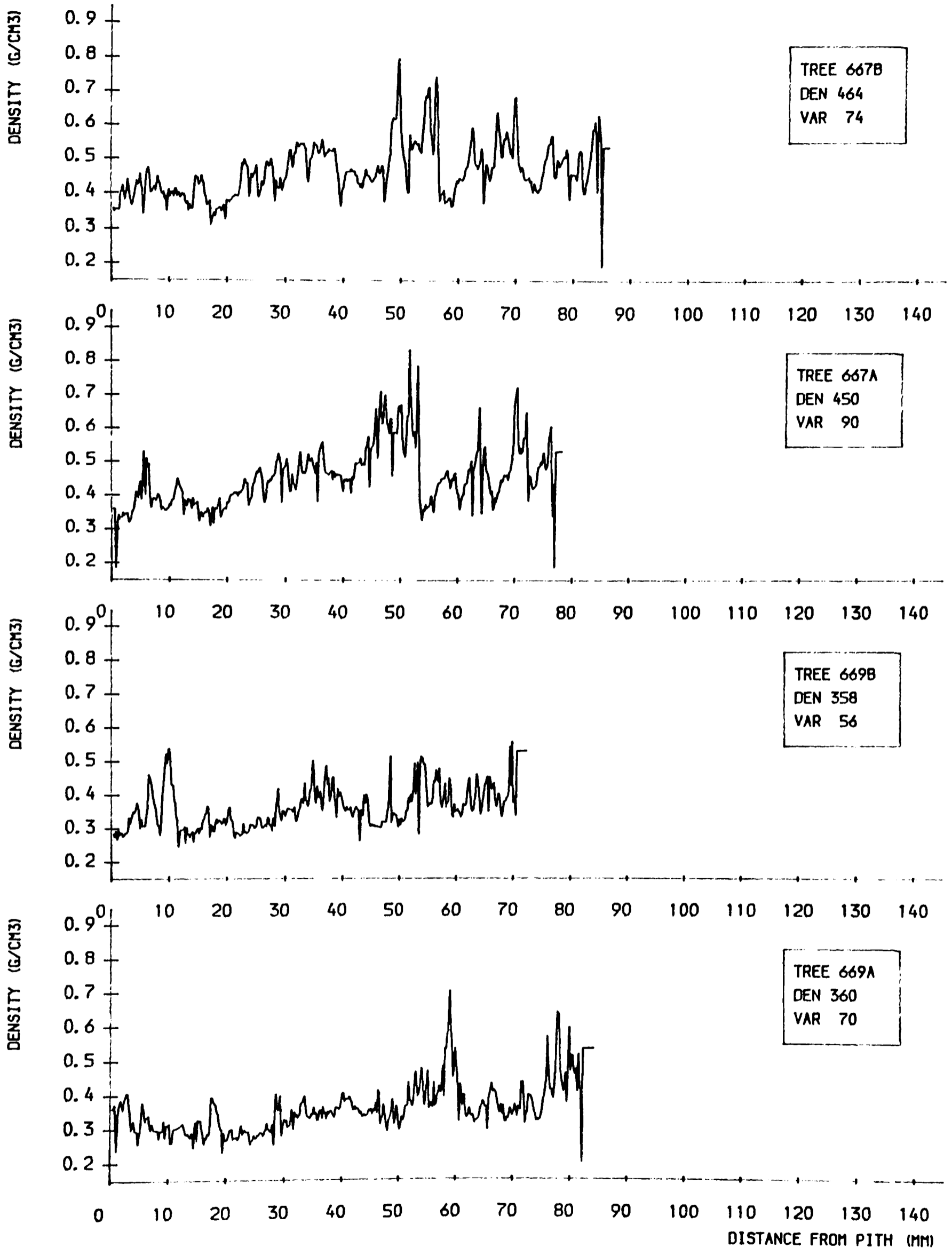


Figure 1.15 Wood density variation of two radii from each of two trees of the Guanaja provenance of *P. caribaea* in Malaysia.

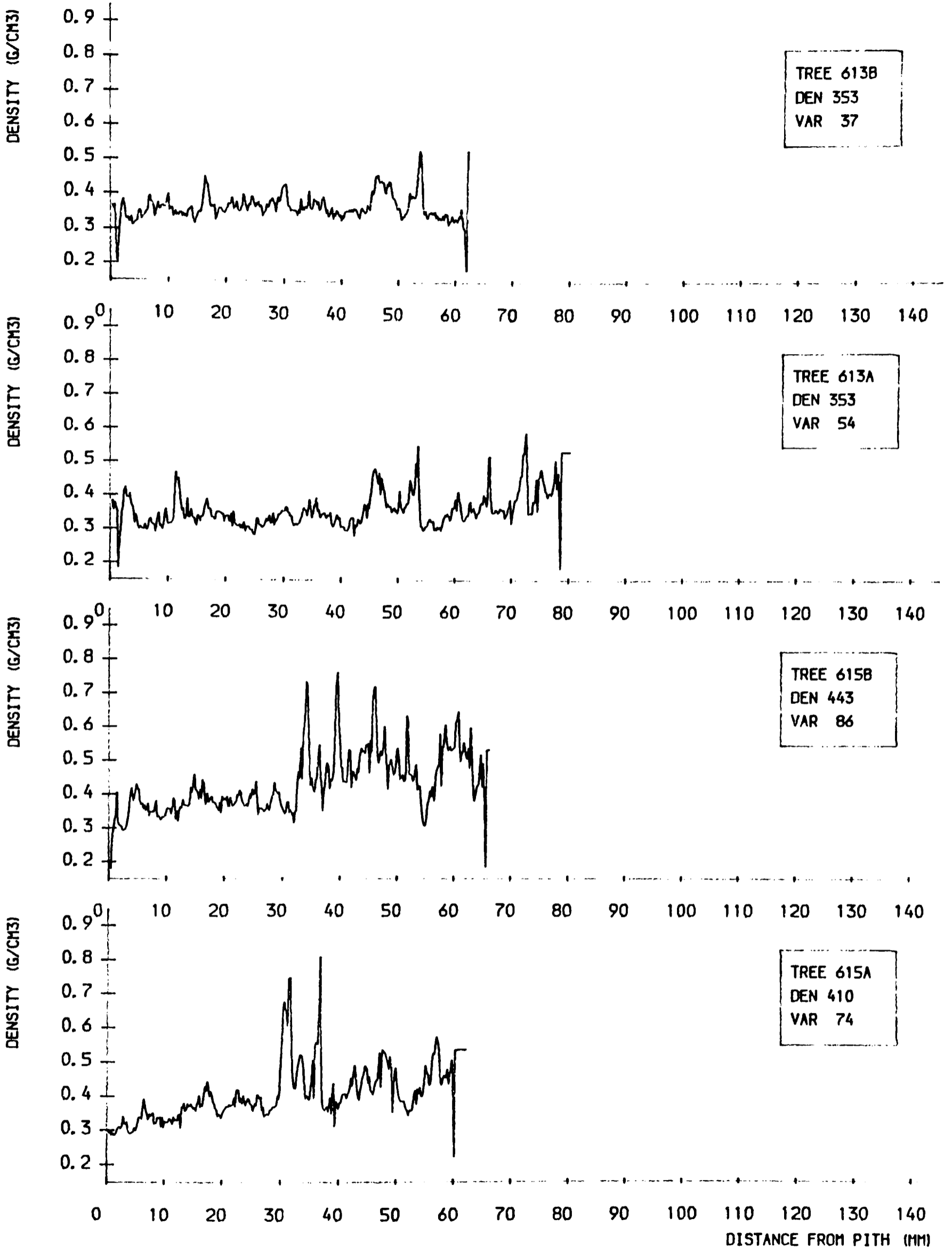


Figure 1.16 Wood density variation of two radii from each of two trees of the Mountain Pine Ridge provenance of P. caribaea in Malaysia.

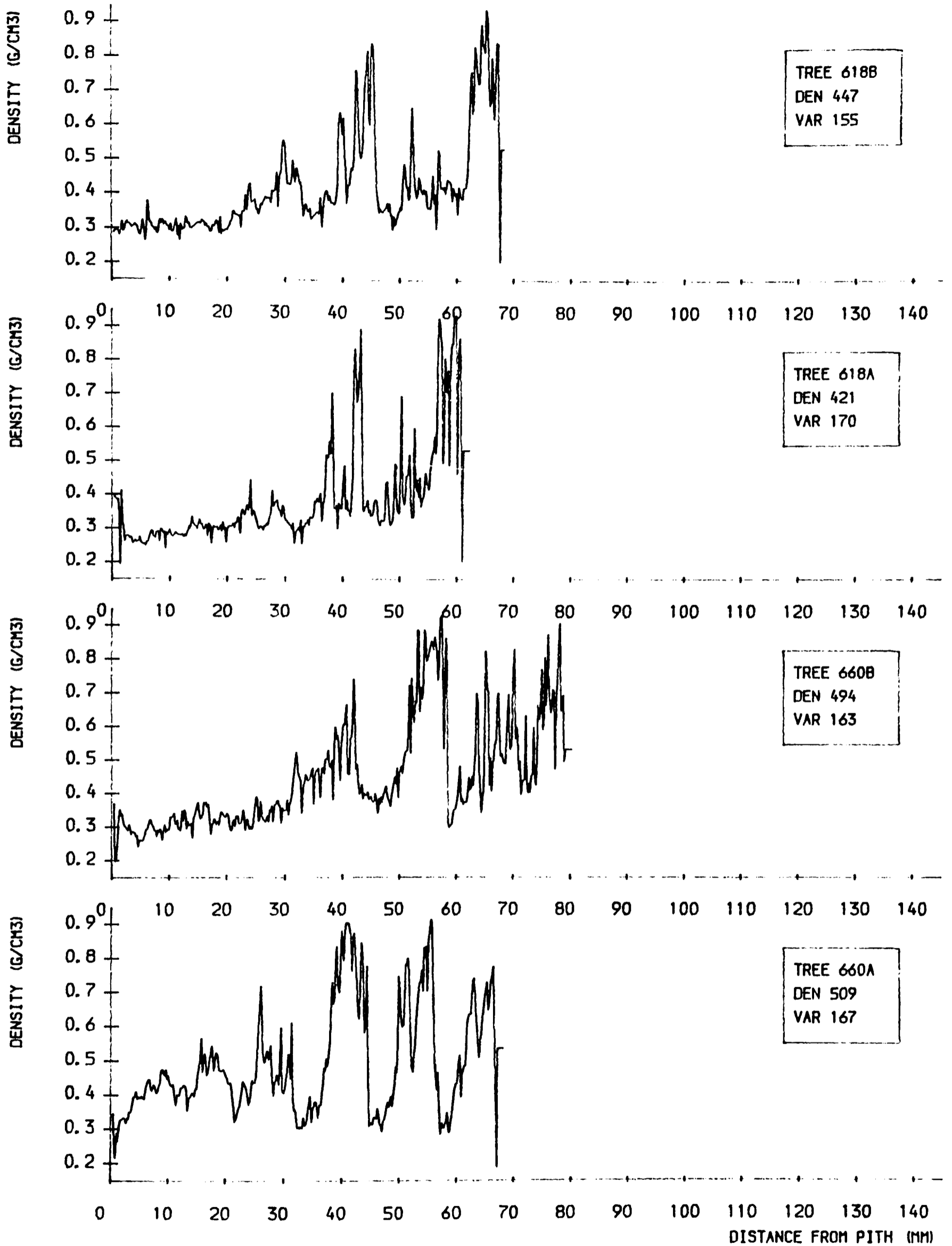


Figure 1.17 Wood density variation of two radii from each of two trees of the Poptun provenance of *P. caribaea* in Malaysia.

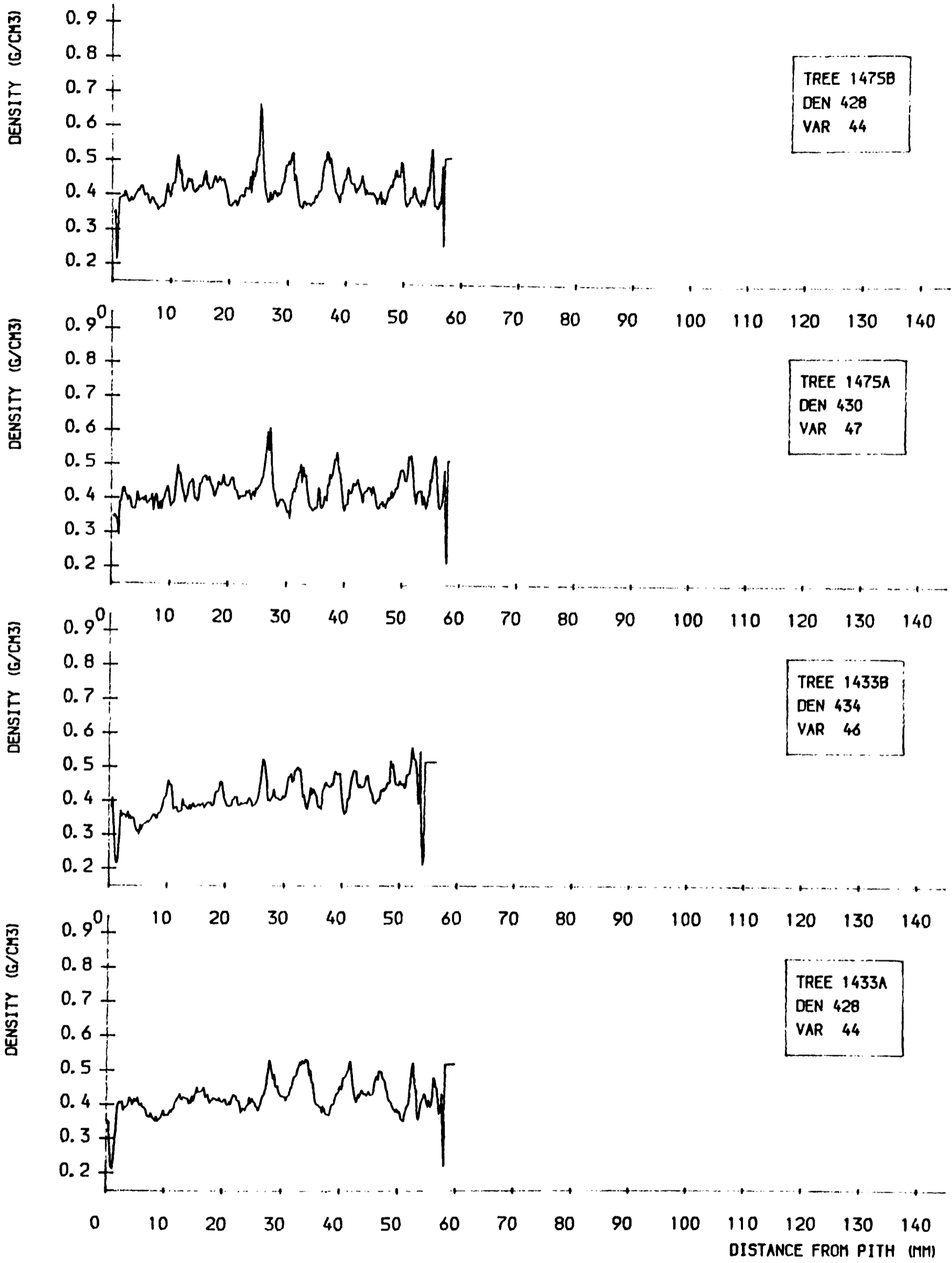


Figure 1.18 Wood density variation of two radII from each of two trees of the Camelias provenance of *P. patula* ssp. *tecunumanii* in Ecuador.

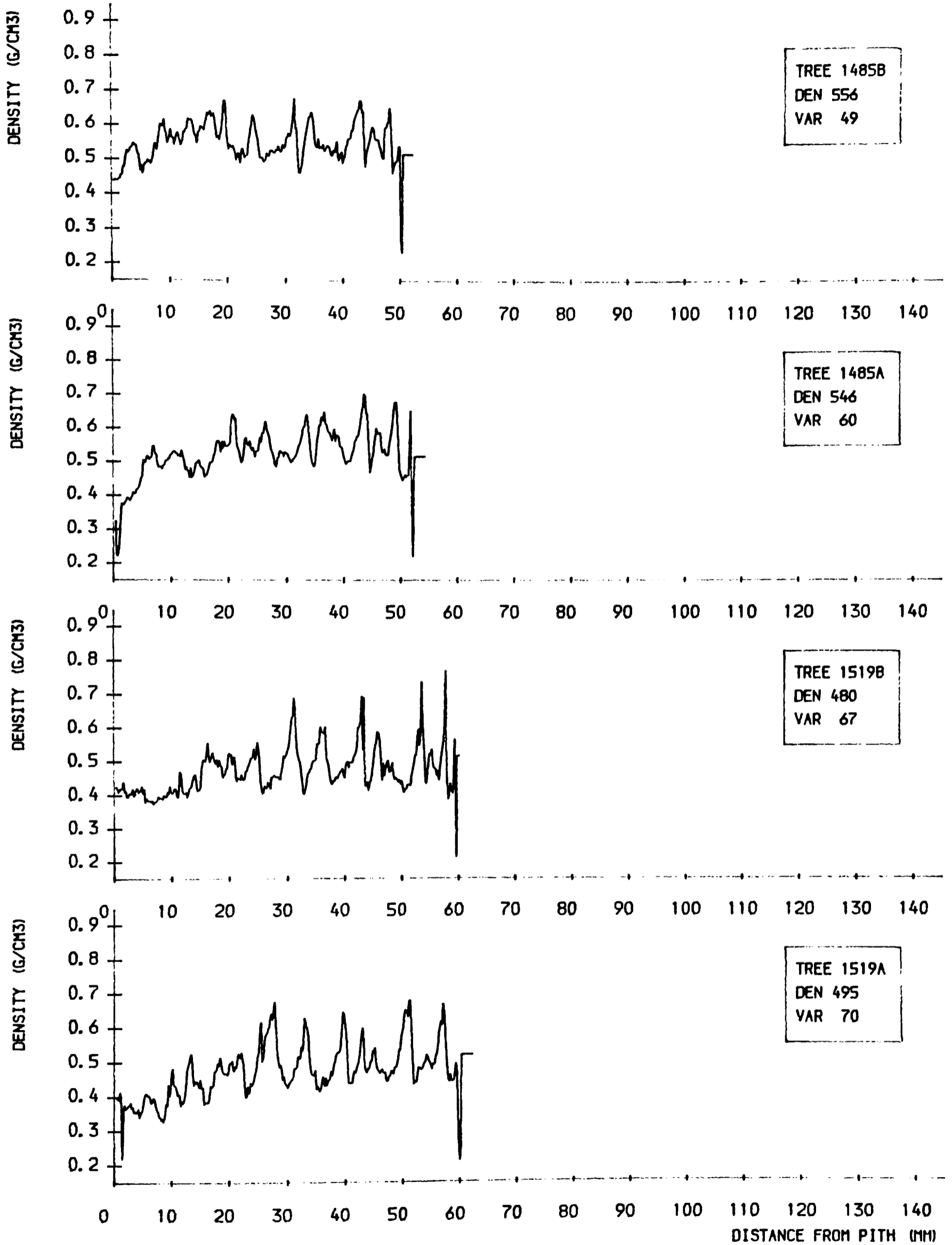


Figure 1.19 Wood density variation of two radii from each of two trees of the Mountain Pine Ridge provenance of P. patula ssp. tecunumanii in Ecuador.

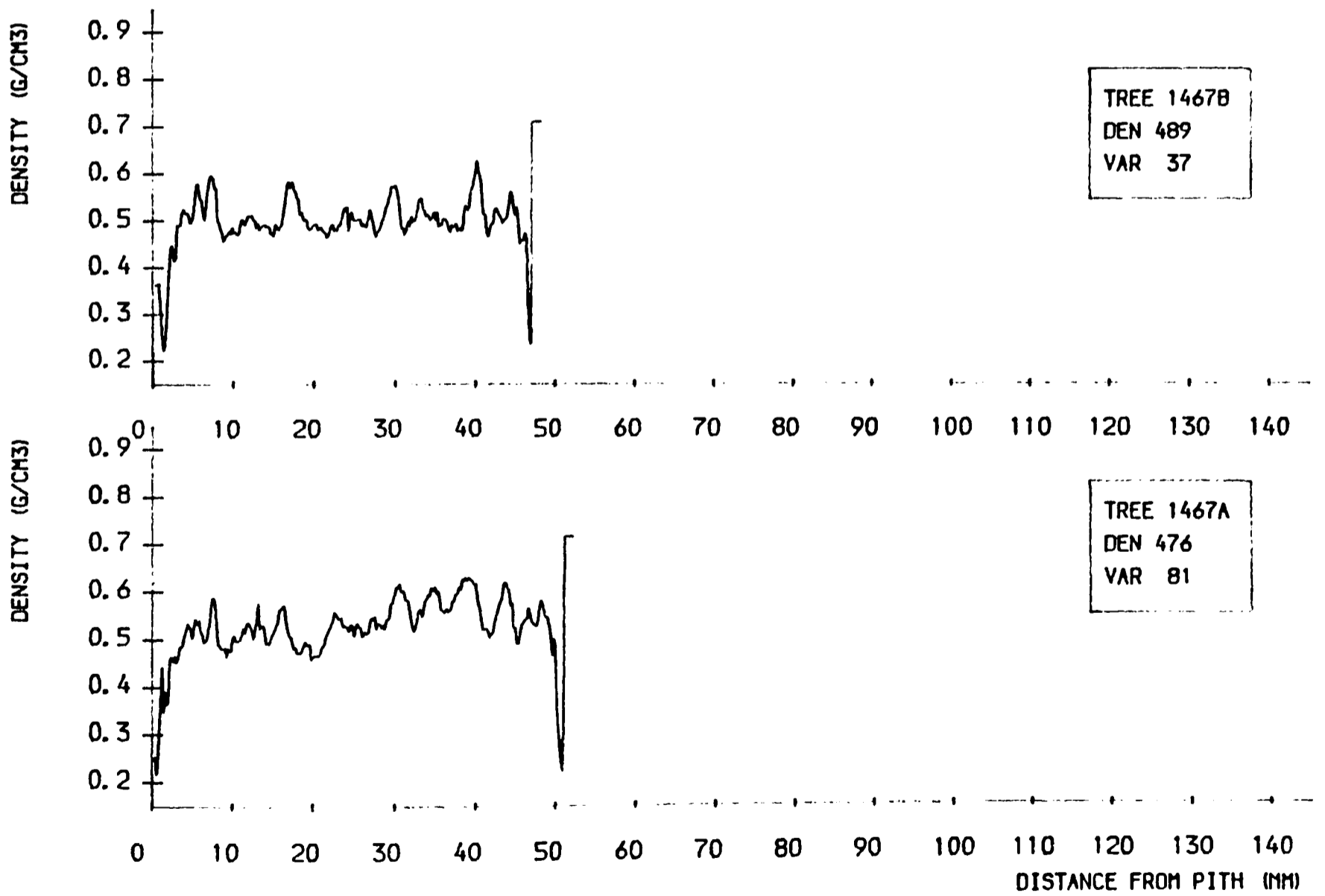


Figure 1.20 Wood density variation of two radii from one tree of the Zamorano provenance of *P. oocarpa* in Ecuador.

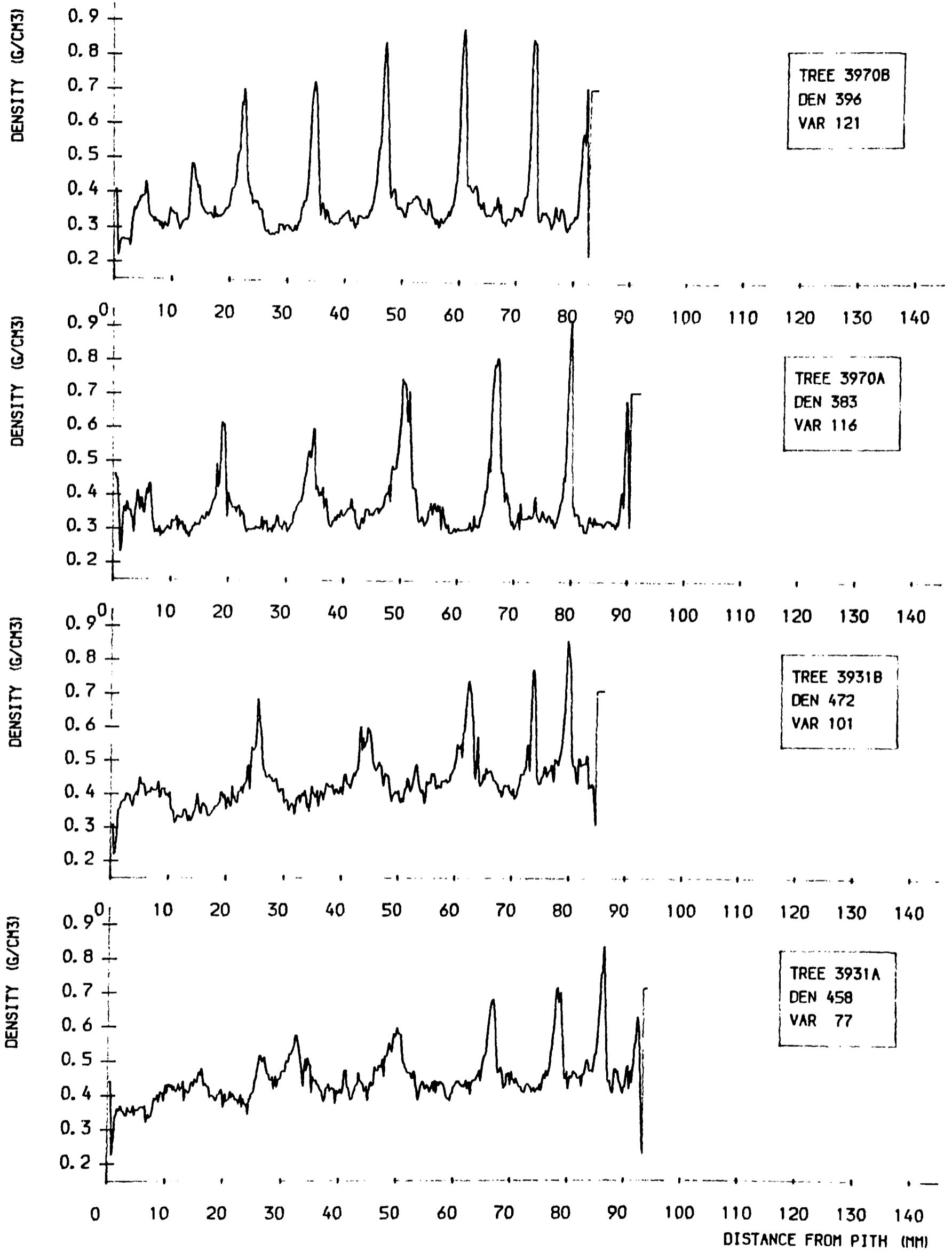


Figure 1.21 Wood density variation of two radii from each of two trees of the Camellias provenance of P. patula ssp. tecunumanii at Wilgeboom.

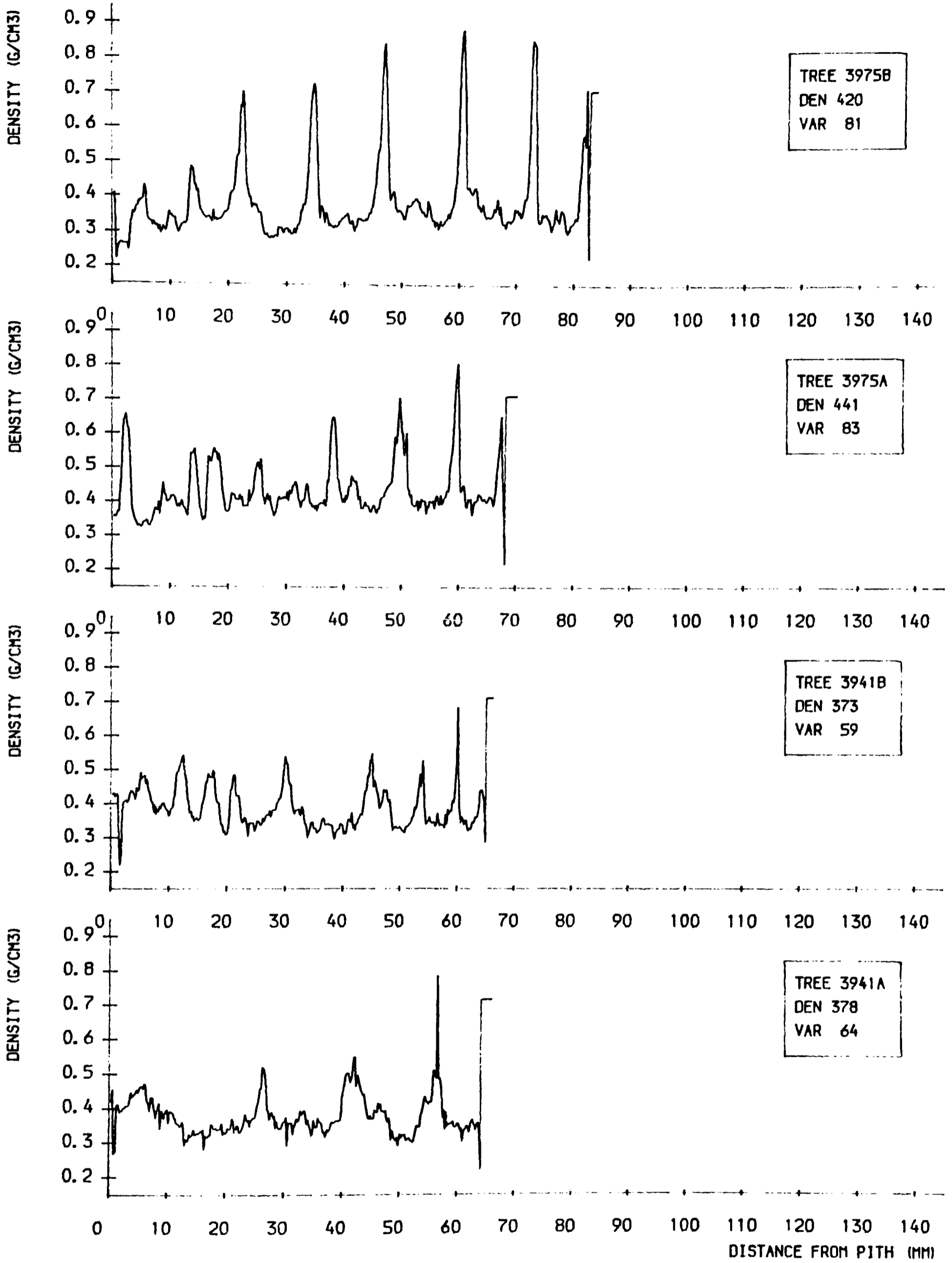


Figure 1.22 Wood density variation of two radii from each of two trees of the Huehuetenango provenance of *P. oocarpa* at Wilgeboom.

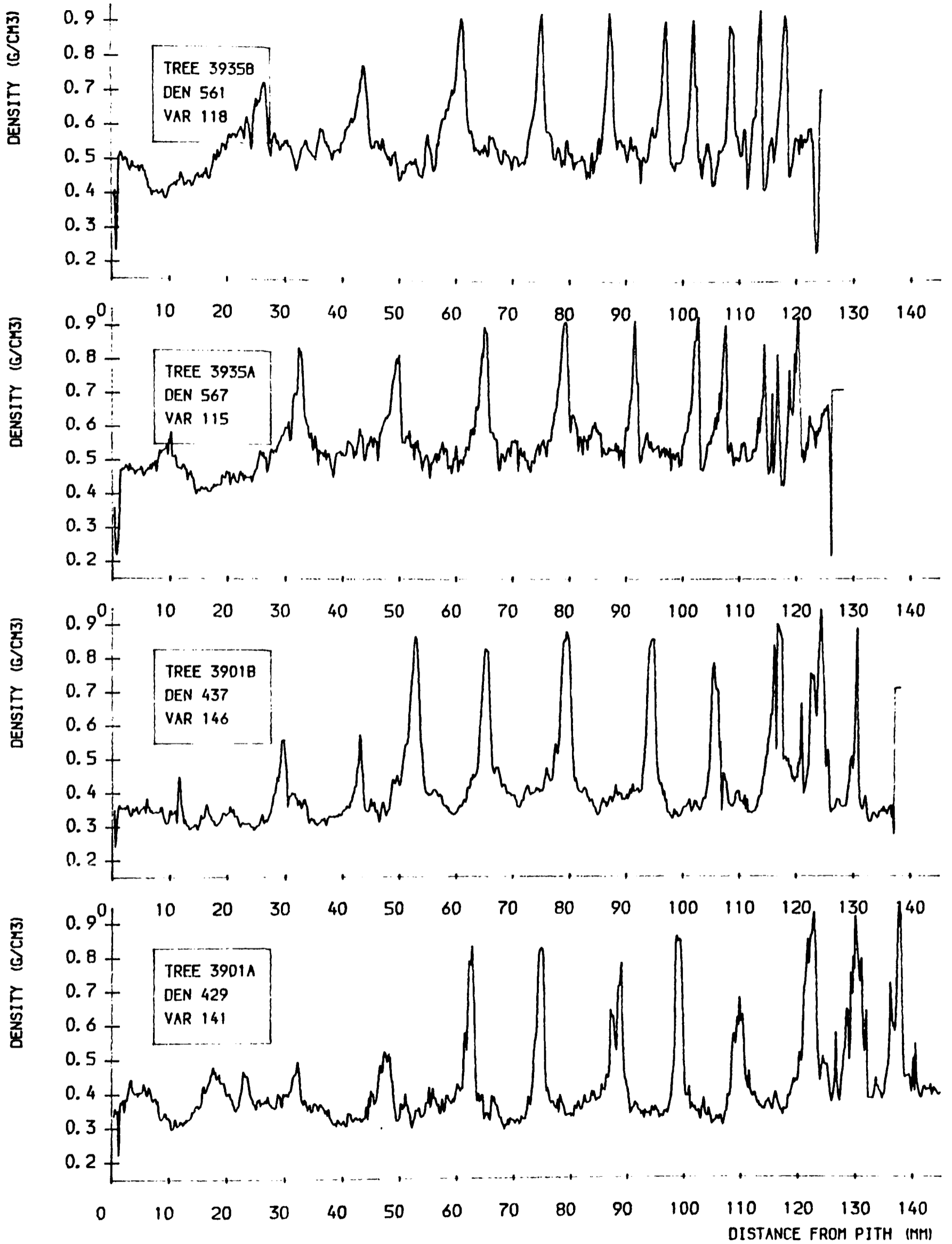


Figure 1.23 Wood density variation of two radii from each of two trees of the Mountain Pine Ridge provenance of *P. patula* ssp. *tecunumanii* at Wilgeboom.

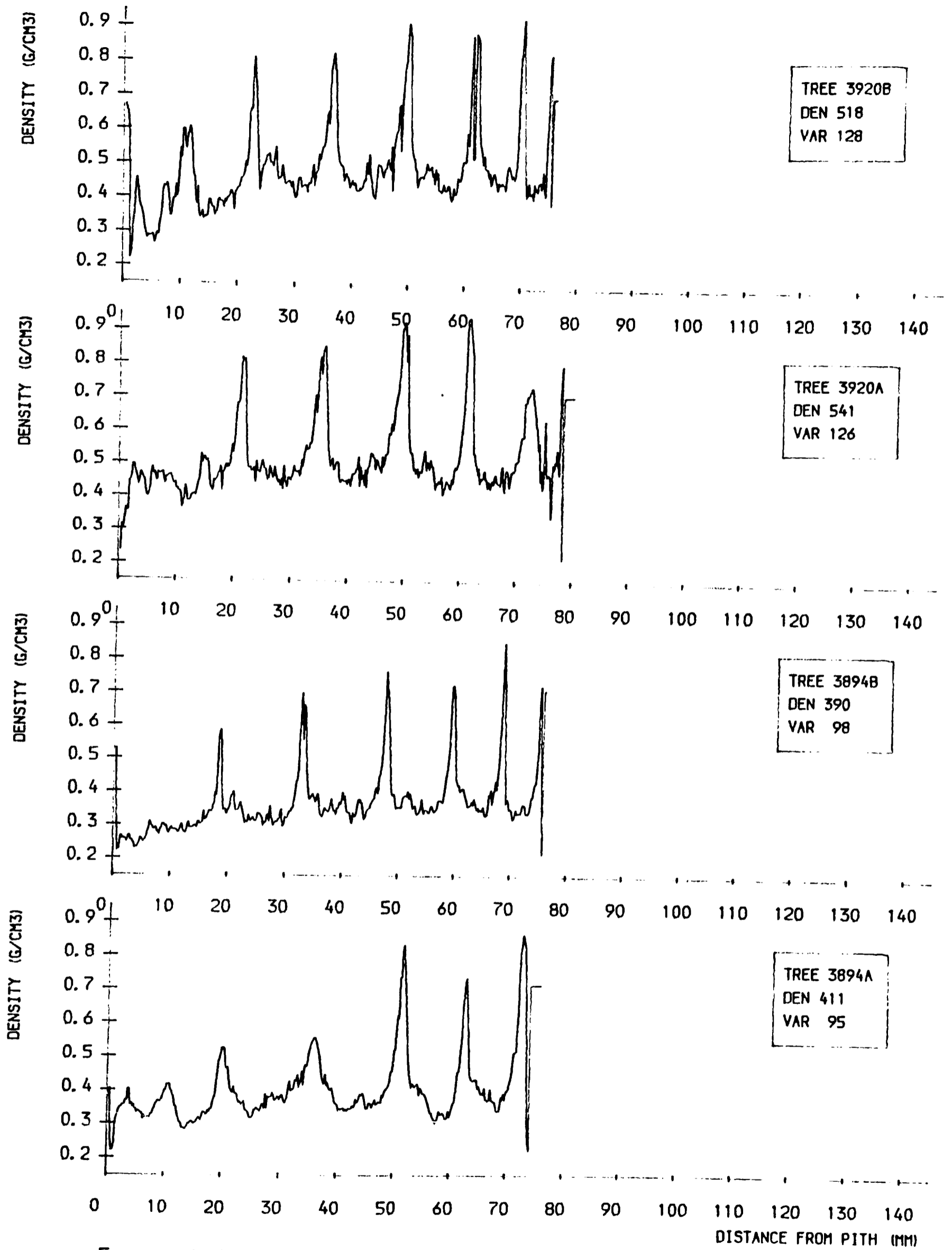


Figure 1.24 Wood density variation of two radii from each of two trees of the Zamorano provenance of *P. oocarpa* at Wilgeboom.

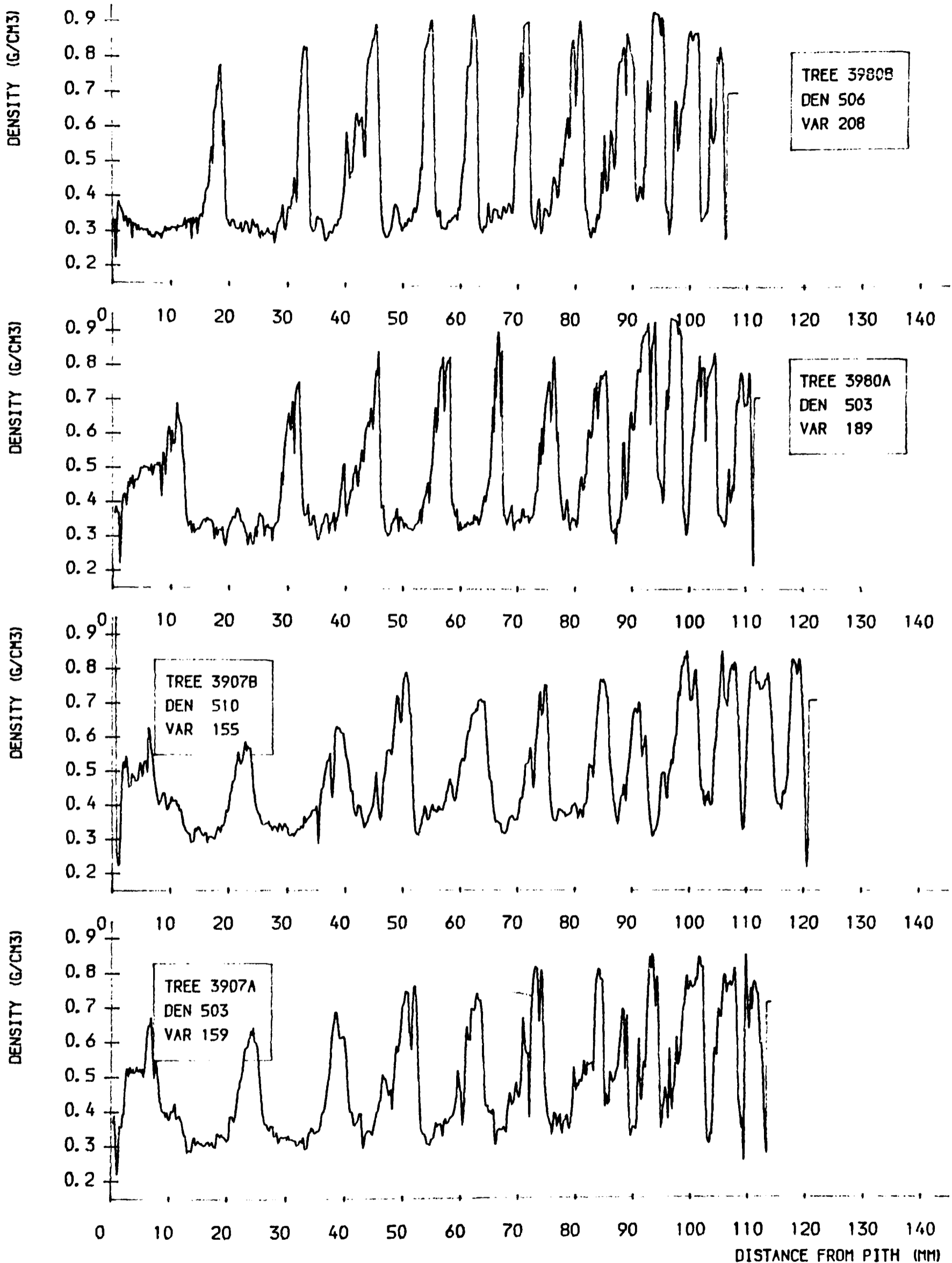


Figure 1.25 Wood density variation of two radii from each of two trees of P. elliotii at Wilgeboom.

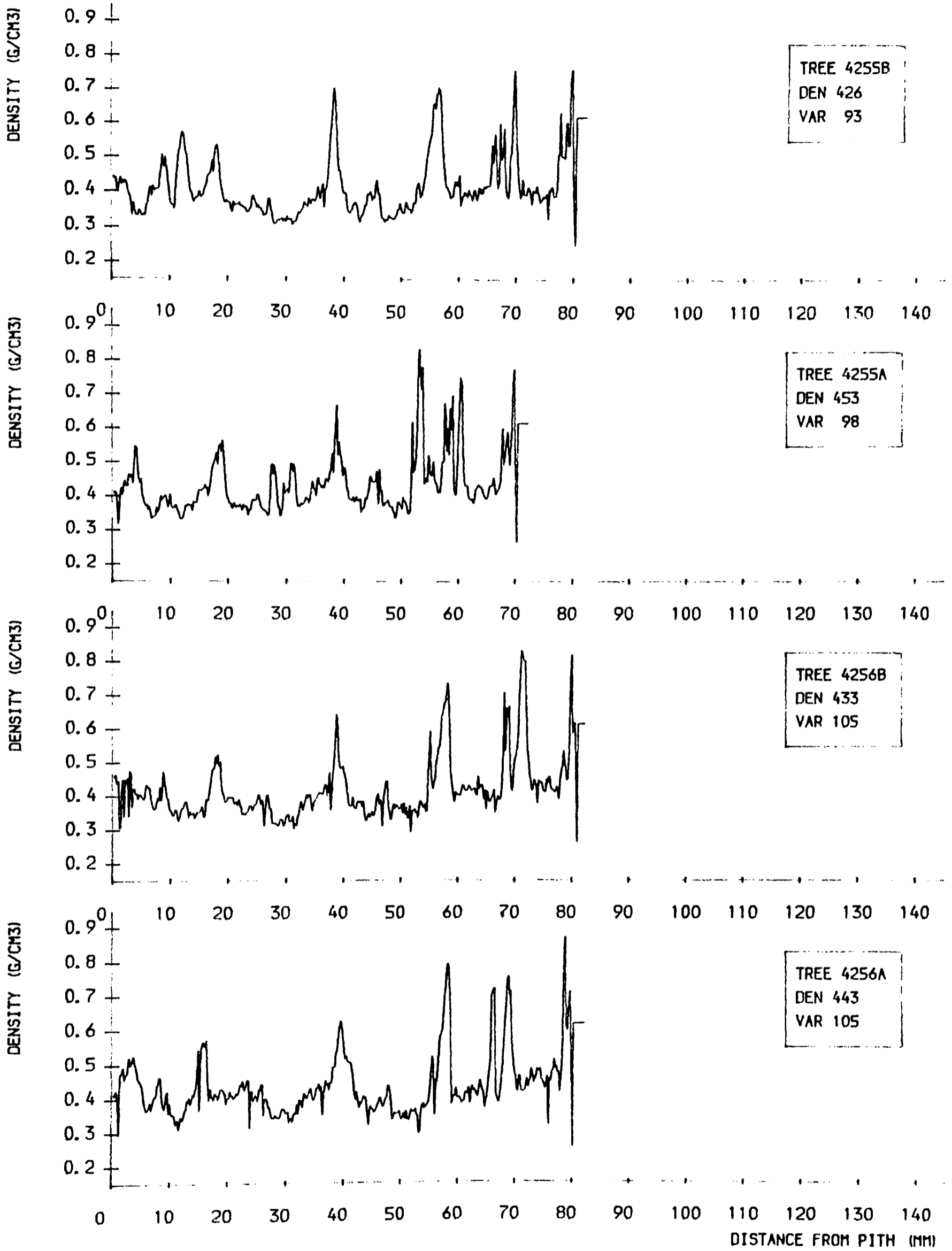


Figure 1.26 Wood density variation of two radii from each of two trees of the Camellias provenance of *P. patula* ssp. *tecunumanii* in Kwambonambi.

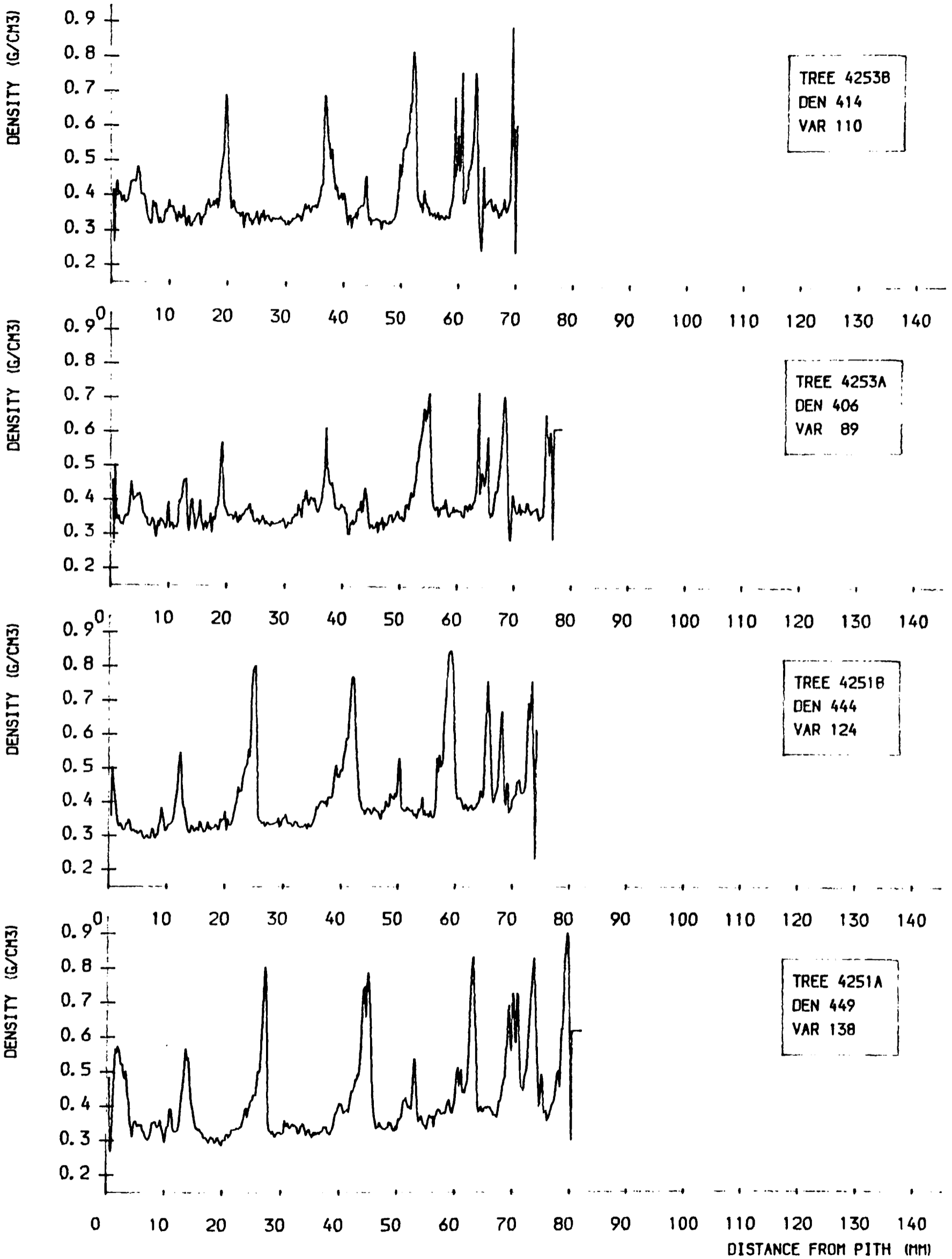


Figure 1.27 Wood density variation of two radii from each of two trees of the Mountain Pine Ridge provenance of *P. patula* ssp. *tecunumanii* in Kwambonambi.

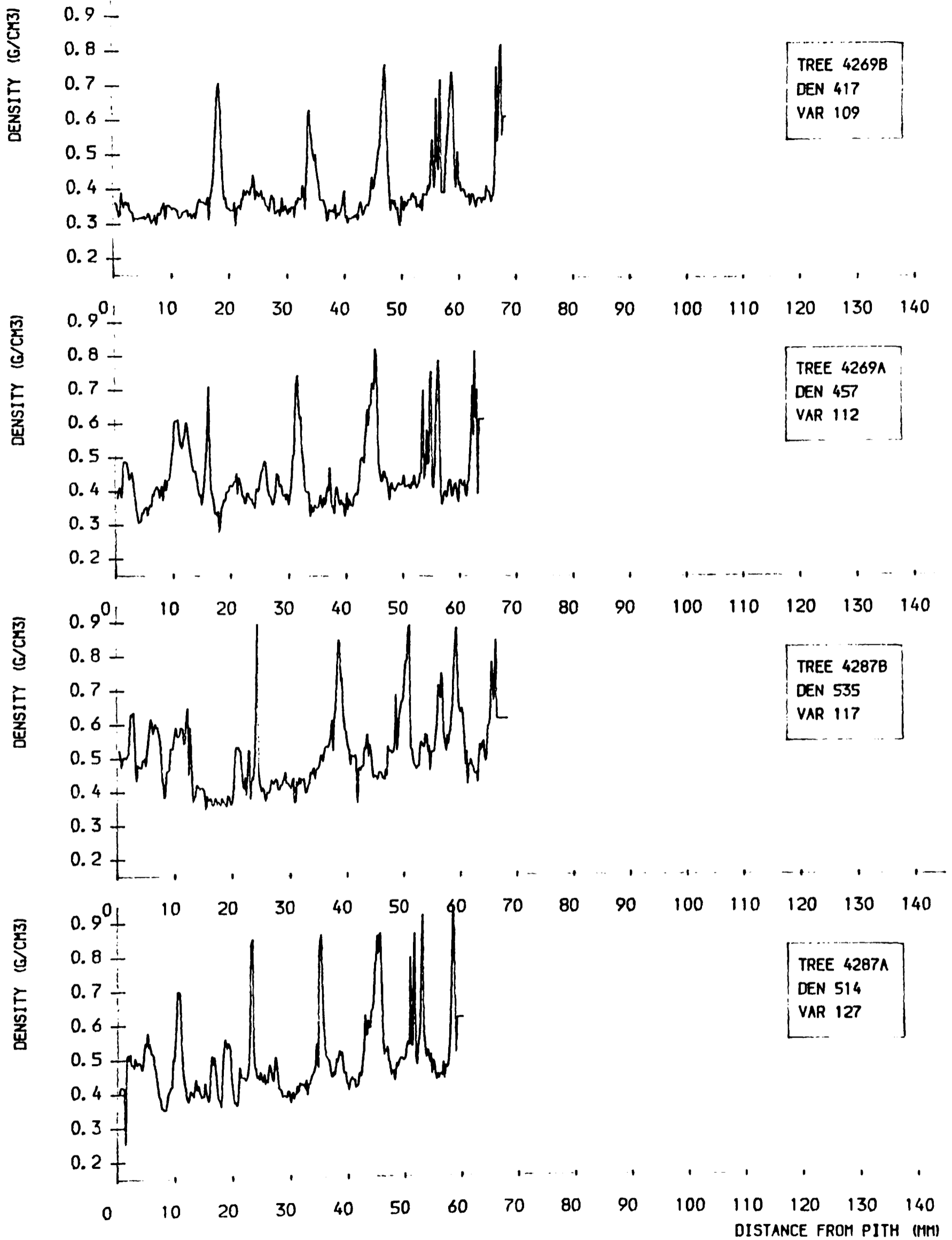


Figure 1.28 Wood density variation of two radii from each of two trees of the Zamorano provenance of *P. oocarpa* in Kwambonambi.

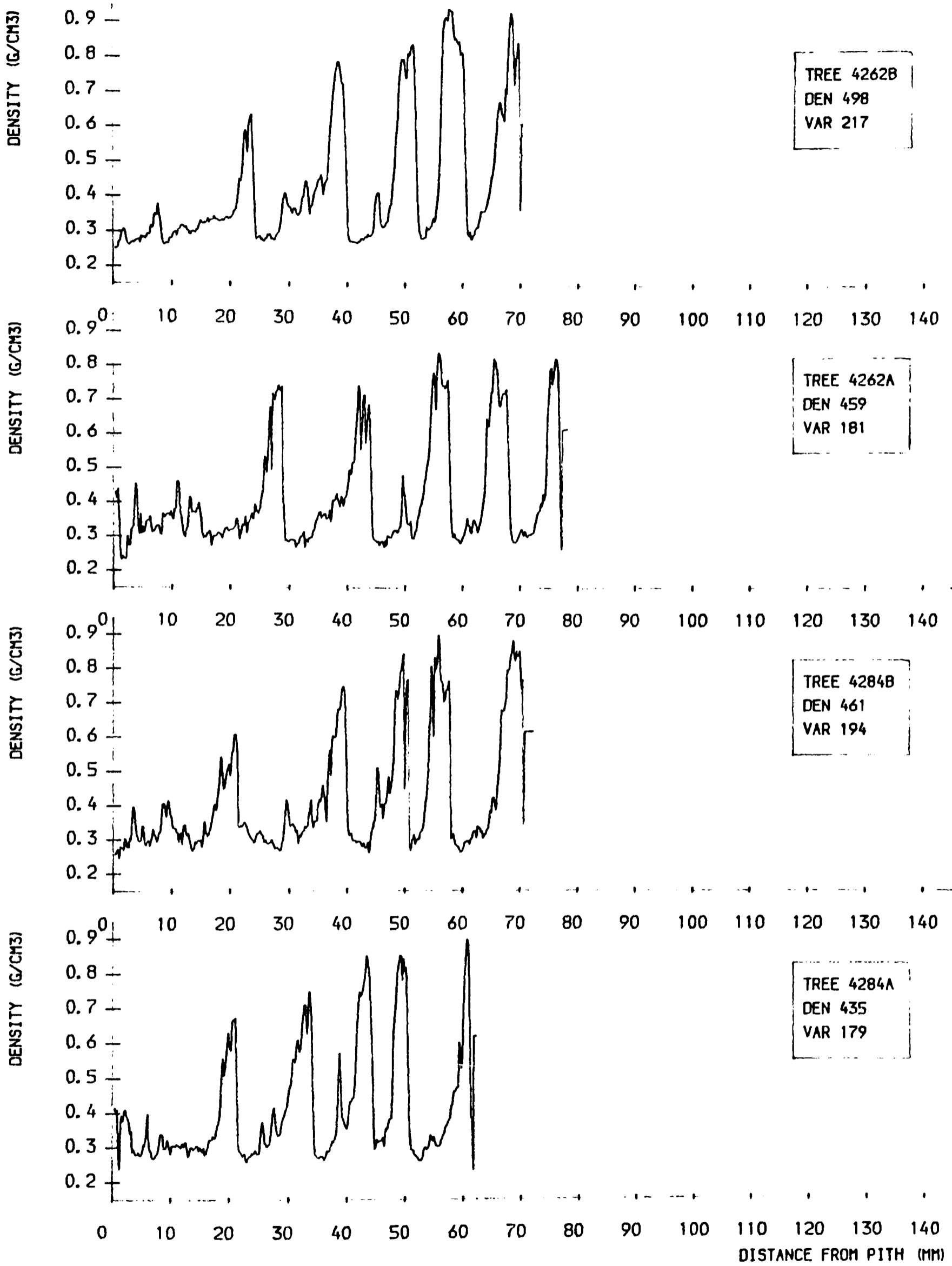


Figure 1.29 Wood density variation of two radii from each of two trees of P. elliotii in Kwambonambi.

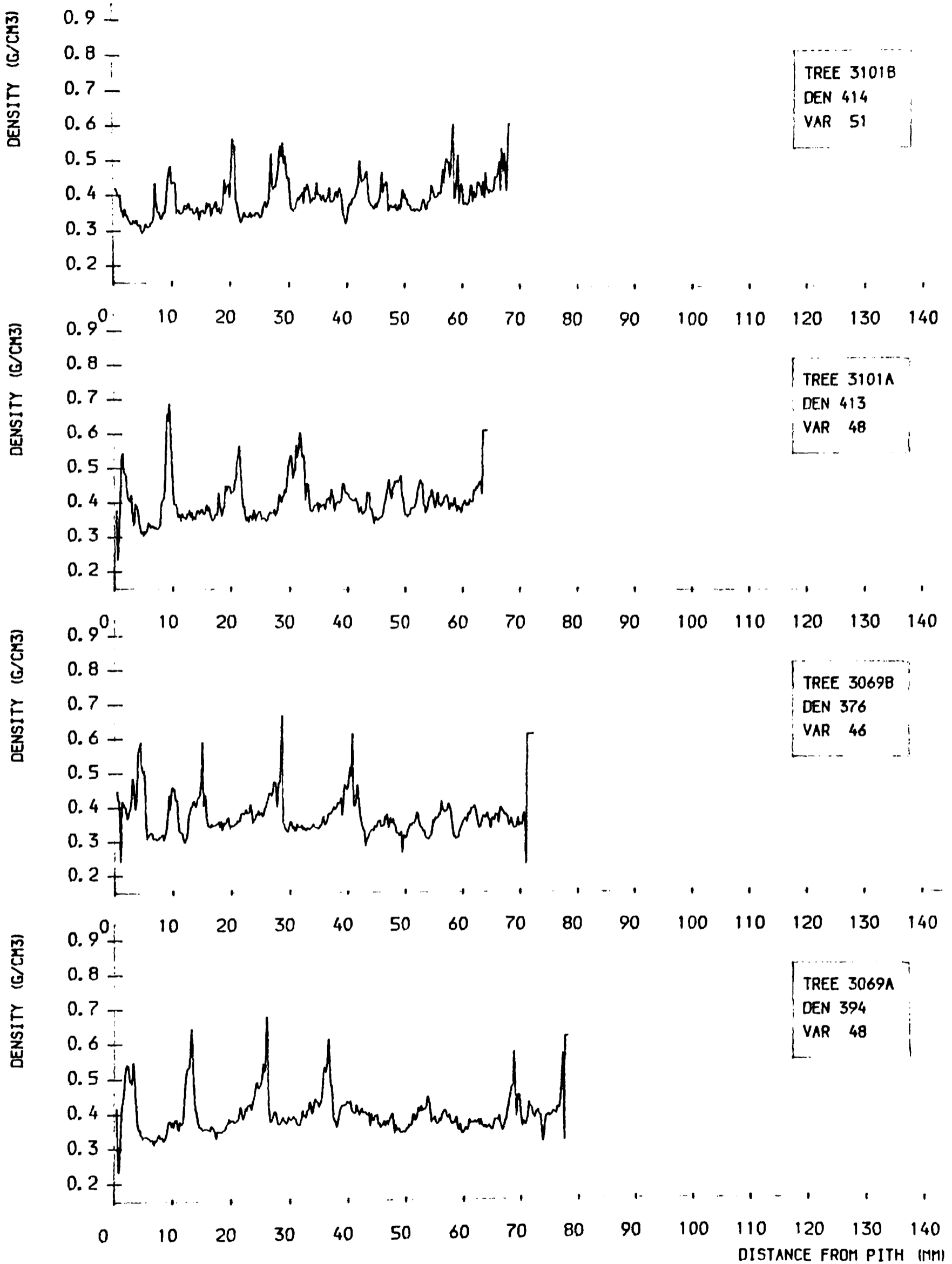


Figure 1.30 Wood density variation of two radII from each of two trees of the Camelias provenance of P. patula ssp. tecunumanII in Kenya.

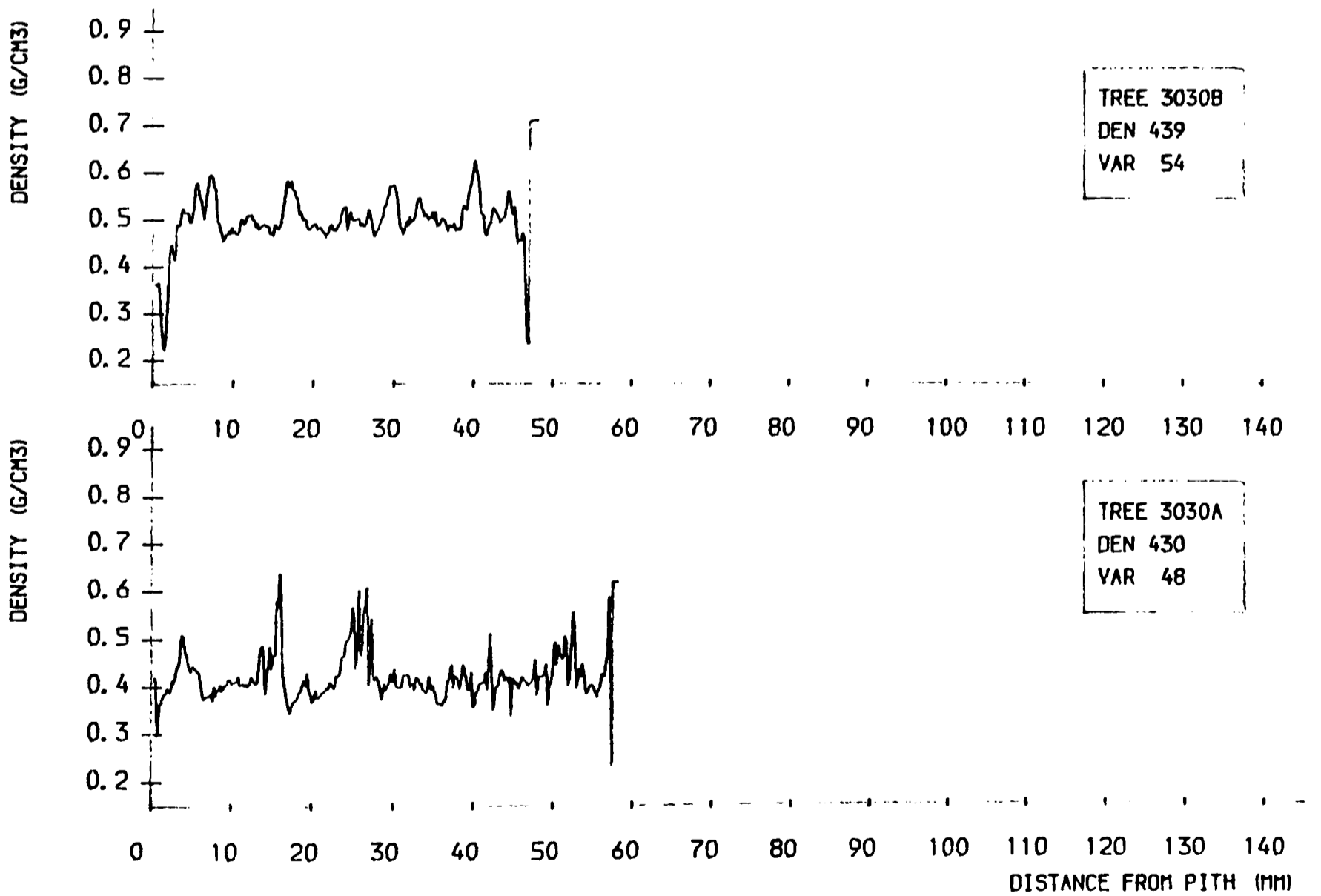


Figure 1.31 Wood density variation of two radii from one tree of the Huehuetenango provenance of *P. oocarpa* in Kenya.

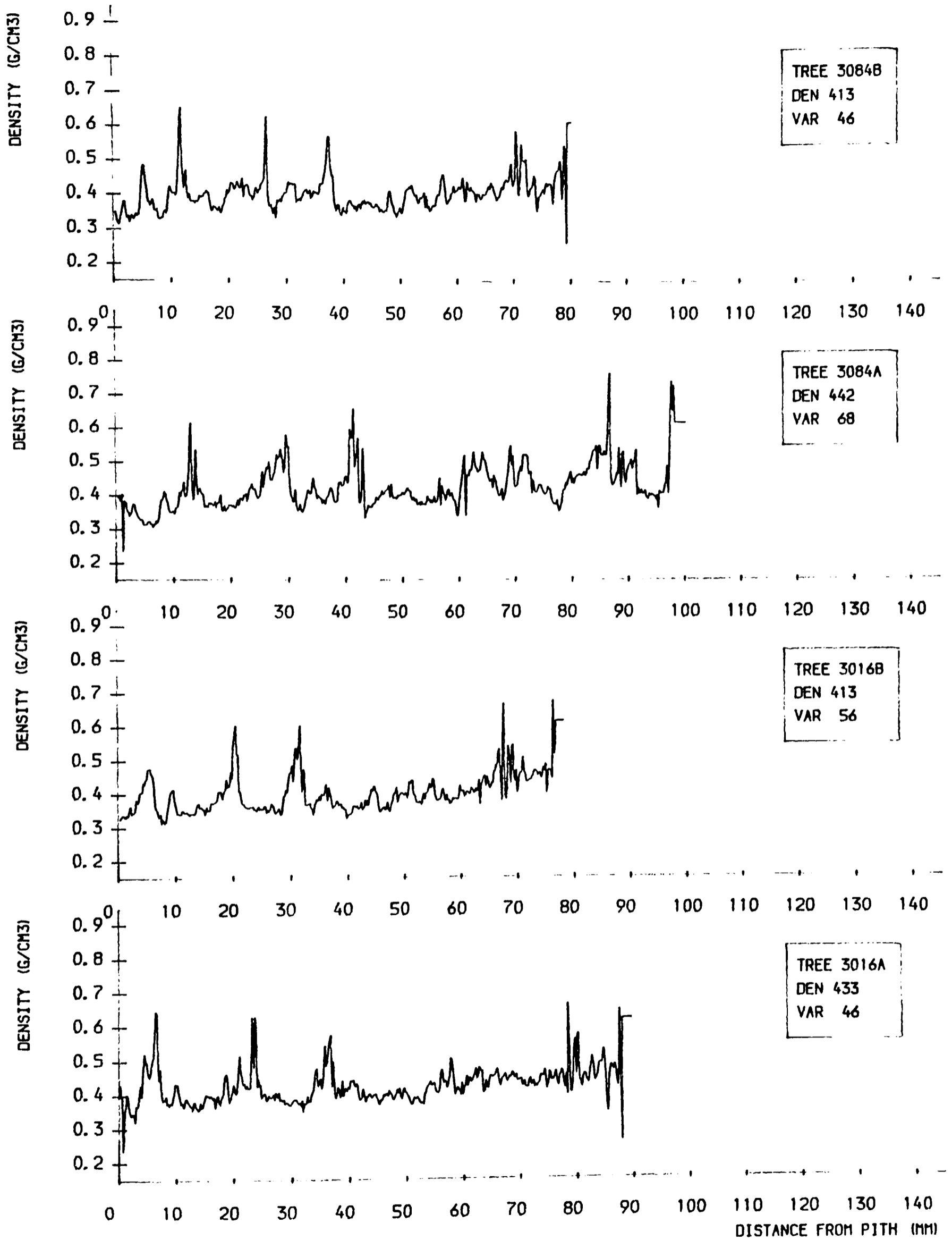


Figure 1.32 Wood density variation of two radii from each of two trees of the Mountain Pine Ridge provenance of *P. patula* ssp. *tecunumanii* in Kenya.

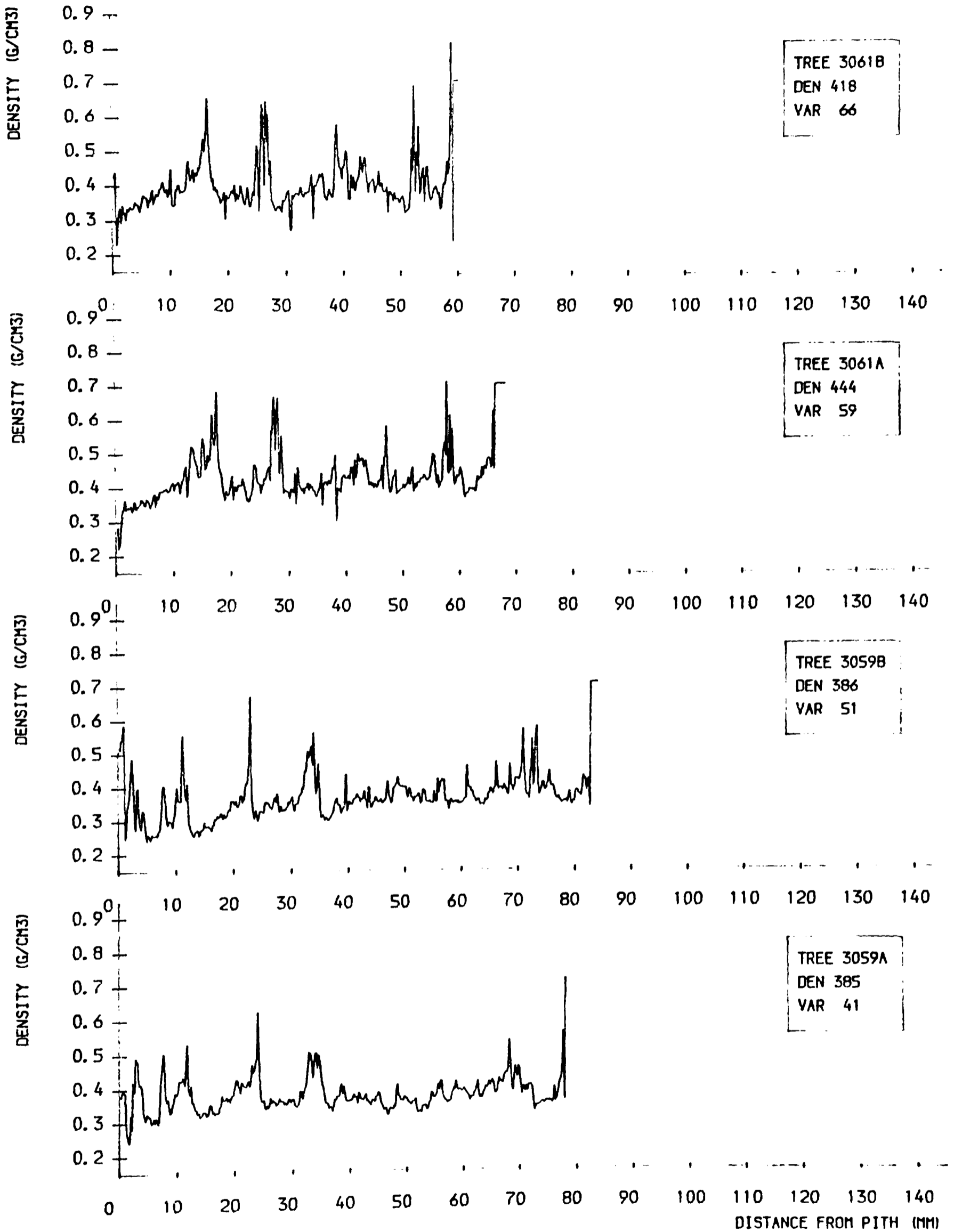


Figure 1.33 Wood density variation of two radii from each of two trees of the Zamorano provenance of *P. oocarpa* in Kenya.

Appendix 2. Corrected site and provenance means for DEN and VAR of P. caribaea, P. oocarpa and P. patula ssp. tecunumanii.

Table 2.1 Corrected site means for DEN and VAR of P. caribaea,
P. oocarpa and P. patula ssp. tecunumanii.

Site	DEN	VAR
<u>P. caribaea</u>		
Anasco-A, Puerto Rico	460	108
Anasco-B, Puerto Rico	436	112
Chati, Zambia	366	57
Loudima, Congo	436	169
San Pedro, Ivory Coast	473	167
Mariti, South Africa	379	53
Bukit Tapah, Malaysia	469	105
Drasa, Fiji	467	141
Nanuku, Fiji	440	117
Beerburum, Australia	451	90
Byfield, Australia	465	113
 <u>P. oocarpa</u> and <u>P. patula</u> <u>ssp. tecunumanii</u>		
Anasco, Puerto Rico	445	79
Conocoto, Ecuador	487	70
Agudos, Brazil	500	100
Ndola East, Zambia	464	91
Wilgeboom, South Africa	480	100
Nzoia, Kenya	456	61

Table 2.2 Corrected provenance means for DEN and VAR of P. caribaea, P. oocarpa and P. patula ssp. tecunumanii.

Provenance	DEN	VAR
<u>P. caribaea</u>		
Alamicamba	432	104
Brus Lagoon	440	106
Byfield	446	113
Culmi	433	129
Guanaja	462	94
Karawala	455	101
Mountain Pine Ridge	450	135
Poptun	439	129
Potosi	460	120
Rio Coco	435	104
Santa Clara	451	123
<u>P. oocarpa</u>		
Huehuetenango	450	78
Lagunilla	483	82
Siguatepeque	467	93
Zamorano	477	80
Zapotillo	480	88
<u>P. patula ssp. tecunumanii</u>		
Camelias	478	80
Mountain Pine Ridge	465	85
Rafael	467	91
Yucul	465	83

Appendix 3. Correlation matrices of DEN and VAR with experimental site and provenance origin parameters.

Table 3.1 Correlation matrix for DEN and VAR of P. caribaea provenances with experimental site and provenance origin parameters (df=620).

	DEN	VAR	PL	PA	PR	PT	SL	SA
VAR	0.701							
PL	0.328	0.362						
PA	0.421	0.833	-0.203					
PR	-0.436	-0.748	-0.357	-0.727				
PT	-0.417	-0.863	-0.617	-0.548	0.677			
SL	-0.206	-0.568	-0.003	-0.010	0.030	-0.007		
SA	-0.872	-0.751	0.047	0.049	-0.097	-0.032	0.047	
SR	0.451	0.044	-0.048	0.008	0.036	0.023	0.043	-0.168
ST	0.716	0.795	-0.037	-0.030	0.061	0.028	-0.524	-0.679
SM	-0.028	0.600	0.015	-0.023	0.006	-0.004	-0.552	-0.203
	SR	ST						
ST	0.111							
SM	-0.219	0.190						

Table 3.2 Correlation matrix for DEN and VAR of P. oocarpa and P. patula ssp. tecunumanii provenances with experimental site and provenance origin parameters (df=196).

	DEN	VAR	PL	PA	PR	PT	SL	SA
VAR	0.489							
PL	-0.374	-0.217						
PA	-0.131	-0.562	-0.227					
PR	-0.168	0.324	0.069	-0.892				
PT	0.292	0.563	0.114	-0.932	0.853			
SL	0.197	0.896	0.018	0.074	-0.023	-0.098		
SA	0.212	-0.568	-0.009	-0.087	0.026	0.113	-0.806	
SR	-0.518	-0.138	-0.028	-0.007	0.005	0.006	0.237	-0.598
ST	-0.505	0.194	-0.003	0.063	-0.017	-0.083	0.441	-0.881
SM	0.242	0.153	0.007	0.064	-0.029	-0.086	0.135	0.135
	SR	ST						
ST	0.783							
SM	-0.773	-0.417						

Appendix 4. Description of assessment procedures for pulp and papermaking traits.

Kappa number

The equivalent of 0.5g bone-dry pulp is treated for five minutes with 0.1N potassium permanganate at 25°C. The reaction is stopped after five minutes by addition of potassium iodide and the liberated iodine is titrated with 0.2N sodium thiosulphate. This gives the permanganate number which is converted to an estimated Kappa number by means of a graph. From the estimated Kappa number, the mass of pulp required to obtain 50% consumption of KMnO_4 is calculated. The number of millilitres of 0.1N KMnO_4 consumed in ten minutes by 1.0g bone-dry pulp at 25°C is known as the Kappa number.

Screened yield(%)

The pulp is screened using a mesh screen. The air dry weight is then converted to oven dry weight using a ratio of oven dry to air dry weight derived from previous samples. The oven dry weight of pulp is then divided by the oven dry weight of wood chips in the cook. This number multiplied by 100 is the screened yield(%).

Reject yield(%)

The pulp that fails to pass through a mesh screen is collected and oven dried at 105°C for twenty four hours. The oven dry weight of the reject pulp is then divided by the oven dry weight of wood chips in the cook. This number multiplied by 100 is the reject yield(%).

Total yield(%)

The total yield(%) is the sum of the screened yield(%) and the reject yield(%).

Spent liquor(AA) and Spent liquor(Na₂S)

These values are derived by chemical analyses of the black liquor following the pulping process. The procedures and reagents used are done to determine the amount of active alkali and sodium sulphide that remain in the black liquor.

%Total solids

A known weight of spent liquor is oven-dried at 105°C to constant weight and solids calculated from these weights.

Wetness

The Schopper-Riegler method was used to determine wetness. A known volume of pulp in aqueous suspension was drained through the fiber mat formed on a wire screen during the test into a funnel provided with a bottom and side orifice. The filtrate collected from the side orifice was measured in a special cylinder graduated in Schopper-Riegler(SR) units. A discharge of 1000ml corresponds to zero SR units and zero discharge to 100 SR units. One SR unit therefore corresponds to 10ml.

Canadian standard freeness(C.S.F.)

A liter of water with 3.0g of pulp was enclosed in a bronze cylindrical chamber of 10.2cm diameter whose bottom consisted of a perforated plate with numerous closely spaced small holes. When the petcock in the lid of the cylinder was opened, the water in the pulp drained down through the plate into a conical catch vessel. In the bottom of the vessel was a small hole having a diameter of 3.05mm. Above the hole was a 12.7mm side outlet. The first flush of water flooded the bottom of the cone and the excess flowed out through the large side orifice. The excess or "free" water was caught in a graduated cylinder and its volume was measured. The number of ml corrected for a temperature of

20°C was the C.S.F.

% Stretch

From the test sheets, ten test pieces were cut to a dimension of 15mm in width and 230mm in length. The test piece was clamped in a tensile testing apparatus designed to extend at a constant rate of elongation. The stretch was measured as the length of elongation at the time of break and % stretch is this length divided by the total length of the test piece multiplied by 100. The procedure was repeated for the ten test pieces and a mean value was derived.

Breaking length

This value is derived by dividing the tensile strength by the basis mass (g m^2).

Burst index

From the test sheets, test pieces at least 65 x 65mm were cut. The test piece was clamped in a Mullen Burst Tester. Hydrostatic pressure was applied at a controlled increasing rate through a rubber diaphragm to a circular area of the test piece. The area of the test piece was held rigidly at the circumference but was free to bulge under the increasing pressure. The hydrostatic pressure required to produce rupture of the test piece is the burst index. The procedure was repeated on ten test pieces and a mean value was derived.

Tear index

From the test sheets, test pieces were cut to a dimension of 50mm in width by 65mm in length. Four of these test pieces together were torn through a fixed distance using the Elmendorf single type tear tester. The internal tear resistance was determined

from the average tearing force as measured by the Elmendorf tester and the number of test pieces(4). The internal tear resistance was then multiplied by 100 and divided by the grammage expressed in grams per square meter and this value is the tear index. The procedure was repeated on ten sets of test pieces and a mean value was derived.

Bulk specific

This test involves the use of a dial micrometer to measure the thickness of a single sheet when a specified static load is applied over a specified area.

Porosity

The test piece is clamped between the jaws of the porosity head and compressed air, at a controlled pressure, is applied to the face of the test piece. The flow of air escaping through the test piece is indicated on one of the flow meters.

Tensile energy absorption(T.E.A.)

This test was performed at the same time as % stretch. The total work done per unit area when elongating the test piece to the moment of rupture was the T.E.A. The procedure was repeated on ten test pieces and a mean value was derived.

Appendix 5. Data for micropulping assessment of pine species/
provenances in South Africa.

Table 5.1 Data for micropulping of pine species/provenances in the Eastern Transvaal, South Africa.

Provenance ¹ (class)	No.	Pulping ²							
		KN	SY	RY	TY	AA	NA	TS	SG
CAM-H	37	50.5	37.07	0.51	37.58	17.6	7.49	12.05	1.071
CAM-L	38	76.4	42.20	1.79	43.99	19.59	7.04	11.64	1.068
MPRT-H	39	54.6	37.42	1.23	38.65	17.60	6.68	12.05	1.070
MPRT-L	40	76.8	41.89	2.23	44.12	19.90	6.74	12.81	1.070
PEL2-H	41	79.9	41.39	2.60	43.99	19.90	6.74	12.80	1.070
PEL2-L	42	82.1	43.73	3.87	47.60	19.74	6.42	12.93	1.068
RAF-H	43	54.7	44.29	1.29	45.58	18.52	7.04	12.21	1.070
RAF-L	44	52.5	40.71	0.96	41.67	18.37	6.74	12.46	1.070
YUC-H	45	55.4	33.49	2.62	36.11	18.37	6.74	12.91	1.070
YUC-L	46	52.6	40.87	2.08	42.95	18.67	7.34	12.43	1.070
ALA-H	47	55.5	41.51	0.72	42.23	17.75	6.12	13.01	1.073
ALA-L	48	50.9	41.01	0.68	41.69	18.06	6.12	12.01	1.073
BYF-H	49	53.3	43.46	0.80	44.26	18.98	6.44	12.96	1.073
BYF-L	50	54.0	40.38	1.71	42.09	18.98	7.04	12.78	1.072
GUA-H	51	53.7	43.09	0.74	43.83	17.60	6.62	12.87	1.072
GUA-L	52	53.4	42.22	1.05	43.27	18.37	6.74	13.22	1.073
MPRC-H	53	55.2	40.22	1.93	42.15	18.98	7.36	13.33	1.071
MPRC-L	54	50.9	41.23	0.76	41.99	18.67	7.04	12.96	1.073
PEL1-H	55	51.3	39.12	0.83	39.95	19.28	6.12	13.25	1.072
PEL1-L	56	54.4	30.44	1.65	32.09	19.44	6.74	13.89	1.068
STA-H	57	51.7	42.57	0.83	43.4	18.98	5.52	12.98	1.073
STA-L	58	55.3	39.38	0.89	40.27	19.13	5.50	13.14	1.072

Provenance ¹ (class)	No.	Paper-making ²								
		TS	CSF	S	BL	BI	TI	BS	P	TEA
CAM-H	37	23.0	540	3.0	8990	5.68	9.8	1.56	1442	113.7
CAM-L	38	19.5	607	2.6	9170	5.40	9.4	1.59	3338	94.7
MPRT-H	39	24.5	515	2.4	8340	5.54	9.9	1.61	1442	85.0
MPRT-L	40	20.5	590	3.0	9480	5.62	8.1	1.56	3224	113.4
PEL2-H	41	17.0	660	3.8	7420	5.80	10.8	1.74	6374	128.8
PEL2-L	42	18.0	640	3.1	8620	5.58	7.3	1.69	3298	101.2
RAF-H	43	30.0	427	2.8	9350	5.72	9.2	1.56	944	100.7
RAF-L	44	26.0	493	3.2	9010	5.94	8.9	1.54	1294	121.4
YUC-H	45	27.0	477	2.8	8800	5.80	10.3	1.54	1436	125.2
YUC-L	46	25.0	505	2.8	9740	5.51	8.6	1.53	1292	106.4
ALA-H	47	29.5	515	2.8	9330	6.19	7.3	1.48	868	116.3
ALA-L	48	24.0	525	3.2	8330	6.54	8.1	1.50	1212	111.5
BYF-H	49	19.0	600	3.3	7500	8.14	10.6	1.61	9940	107.6
BYF-L	50	22.5	530	3.2	9390	6.39	8.1	1.49	9390	129.3
GUA-H	51	21.5	570	3.4	9720	5.90	7.1	1.52	2626	141.9
GUA-L	52	20.5	590	3.6	8500	6.01	8.5	1.49	1000	135.4
MPRC-H	53	18.5	630	3.3	8140	5.78	8.1	1.53	4008	114.7
MPRC-L	54	20.5	590	3.2	8420	5.88	7.0	1.45	1854	110.9
PEL1-H	55	26.5	485	3.3	9410	6.48	10.6	1.57	982	128.0
PEL1-L	56	23.0	540	3.4	9192	6.24	9.6	1.52	1200	135.4
STA-H	57	24.0	525	2.9	9117	5.66	8.2	1.53	1384	110.9
STA-L	58	22.0	560	2.9	9800	5.94	7.1	1.46	712	120.9

¹Provenance details can be found in Table 4.4.

²Description of the pulping and paper-making traits can be found in Table 4.3.

Table 5.2 Data for micropulping of pine species/provenances in Zululand, South Africa.

Provenance ¹		Pulping ²							
(class)	No.	KN	SY	RY	TY	AA	NA	TS	SG
CAM-H	59	56.3	42.36	0.95	43.31	19.74	6.42	12.28	1.070
CAM-L	60	52.6	45.04	0.91	45.95	19.28	6.72	12.67	1.073
CAN-H	61	58.3	39.63	1.10	40.73	18.22	7.42	11.73	1.071
CAN-L	62	62.6	39.06	1.03	40.09	18.53	7.22	11.49	1.070
MPRT-H	63	53.3	40.75	1.23	41.98	19.74	8.86	13.19	1.072
MPRT-L	64	57.1	43.54	0.86	44.40	18.98	6.44	13.60	1.072
PEL-H	65	67.2	42.14	3.74	45.88	17.29	6.42	13.27	1.068
PEL-L	66	59.1	43.22	1.06	44.28	19.44	6.44	13.20	1.071
ALA-H	67	57.1	37.16	1.40	38.56	19.28	6.42	12.77	1.071
ALA-L	68	55.8	40.60	1.58	42.18	18.98	6.12	12.86	1.072
GUA-H	69	53.4	33.12	1.58	34.70	19.76	7.76	12.09	1.067
GUA-L	70	82.1	43.43	5.91	49.34	11.94	5.52	11.17	1.059
MEL-H	71	61.8	38.96	2.19	41.15	18.82	6.42	12.82	1.069
MEL-L	72	63.0	40.35	1.28	41.63	18.67	6.72	12.87	1.070
MPRC-H	73	58.2	34.09	1.35	35.44	18.22	7.29	11.89	1.069
MPRC-L	74	60.0	41.76	2.41	44.17	18.67	6.42	13.15	1.070

Provenance ¹		Paper-making ²								
(class)	No.	TS	CSF	S	BL	BI	TI	BS	P	TEA
CAM-H	59	25.0	505	2.7	9650	6.14	8.2	1.52	878	109.3
CAM-L	60	23.5	533	2.6	9990	6.14	8.2	1.49	1280	108.2
CAN-H	61	26.5	485	2.9	8920	5.69	9.7	1.53	2840	115.3
CAN-L	62	27.0	477	2.8	9950	6.62	9.2	1.57	540	121.1
MPRT-H	63	21.5	570	2.8	9330	5.75	9.1	1.55	2076	103.0
MPRT-L	64	22.0	560	2.7	9200	6.42	8.2	1.52	1656	105.7
PEL-H	65	21.0	580	3.4	8010	5.37	11.0	1.67	2990	116.3
PEL-L	66	22.0	560	3.6	8810	5.85	10.4	1.59	1974	133.8
ALA-H	67	21.0	580	3.2	9530	5.94	8.0	1.53	1392	121.9
ALA-L	68	20.5	590	3.1	9080	5.91	7.6	1.48	652	115.5
GUA-H	69	23.5	533	3.2	8940	5.56	9.3	1.63	1684	119.9
GUA-L	70	18.0	640	2.6	8110	5.63	7.3	1.64	4406	63.3
MEL-H	71	21.0	580	2.9	8440	5.53	9.3	1.58	2192	97.0
MEL-L	72	21.0	560	3.0	8230	5.3	9.3	1.58	1884	102.2
MPRC-H	73	23.0	540	3.2	8420	5.25	8.8	1.54	1600	115.8
MPRC-L	74	20.0	600	3.1	8890	6.10	8.0	1.52	868	110.5

¹Provenance details can be found in Table 4.4.

²Description of the pulping and paper-making traits can be found in Table 4.3.