DENSITY VARIATION WITHIN *COCOS NUCIFERA* STEMS

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SUMMARY

The relation between the anatomy and basic density of **Cocos nucifera** has been determined using material from the stems of a young, mature, and an overmature palm. Changes in basic density within the stem and with age are almost entirely due to the relative abundance of sclerenchyma fibres and ground parenchyma cells and to changes in cell wall thickness, as both cell types retain their vital functions and continue to lay down additional cell wall material for a very long time at all positions in the stem. The variation in both cell types is illustrated with scanning electron micrographs.

INTRODUCTION

The Coconut Palm (*Cocos nucifera* L.) is grown in many Pacific countries for its copra, used in the manufacture of soap and margarine. Large-scale planting programmes were started around the beginning of the present century, continuing after the first world war and ceasing at the time of the great depression. It has been found that, in general, copra production declines after the coconut palm is about 60-70 years old. The palm is then termed "overmature". At the present time several millions of these less productive palms need to be replaced annually. Disposal of the stems presents many problems from the point of view of insect control and pollution. In October 1976 a coconut stem utilisation seminar was held in Tonga to discuss economic uses for the coconut "wood". One of the recommendations of the seminar was that a more thorough understanding of the anatomy and physical properties of *Cocos nucifera* stems was needed.

The physical properties of the mature stem were described by Richolson and Swarup (1977). They showed that the basic density appeared to decrease linearly with increasing height in the stem and increase logarithmically from centre to cortex at any one height. In various unpublished reports it has been shown that the basic density at any particular height tends to increase with age of the palm. For example, A. S. Alston (pers. comm.) found that at a height of about 7 m there was a threefold increase between a young and an overmature palm from the same site. Overall, the range of basic density reported, from 100 to 900 kg/m^3, is vastly greater than that of a "normal" wood (for *Pinus radiata,* 320-500 kg/m^3).

In dicotyledons and gymnosperms growth originates at the vascular cambium so that the trunk simultaneously elongates and increases its girth. Cell wall deposition is

completed relatively quickly, the cytoplasmic contents disappear and the cell dies. Thus no further changes in cell dimensions or wall thickness take place. *Cocos nucifera* is a monocotyledon and its growth pattern is quite different. During the first four or five years the stem expands radially, but all subsequent growth occurs at the apical meristem and the palm then elongates with little further radial growth. There is no vascular cambium and the individual cells continue to live for a very long time, probably for the full life of the palm. During this time anatomical changes can continue to take place. The present paper is largely concerned with changes in the anatomy which affect basic density.

Anatomy

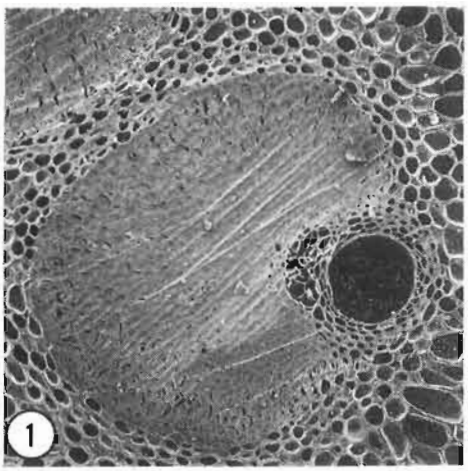
A brief description of the anatomy of *Cocos nucifera* has been given recently by Richolson and Swarup (1977). The stem comprises a central cylinder surrounded by a cortex. The cylinder consists of ground parenchyma tissue in which are embedded the vascular bundles. Near the centre of the stem, the number of vascular bundles per unit cross sectional area is quite low but the number increases rapidly towards the cortex. Within about 75 to 100 mm of the cortex the vascular bundles are very congested, being separated by only very narrow bands of ground parenchyma tissue. This dense region clearly provides the main mechanical support for the palm and Orman (1974) has shown that good quality structural timber from coconut is more or less confined to this zone.

Each vascular bundle consists of xylem, phloem, axial parenchyma and thick walled sclerenchyma fibres. The latter make up the main mass of the bundle and provide the palm's axial strength. Kloot (1952) found that the sclerenchyma fibres have thin walls and large lumens near the centre of the stem (Figs. 2 and 4) but near the cortex they have very thick walls and small lumens (Figs. 1 and 3). He also noted that the ground parenchyma cells become progressively thicker walled and darker in colour from the centre to the periphery of the stem.

The fibre walls are commonly lamellated (Fig. 3) and both the number of lamellae and the total wall thickness vary within any fibre bundle. The walls of fibres close to the phloem tend to be thicker than those near the outside of the bundle and further away from the phloem. Sometimes the outermost fibres of the bundle, those in contact with the ground tissue, have slightly thickened walls.

Scattered throughout the stem are smaller bundles of narrow fibres (Figs. 9 and 10) having no associated vascular tissue. These fibrous strands are most prolific near the centre of the stem but their number per unit area falls off rapidly towards the cortex

FIG. 1 (opposite)—Typical vascular bundle from a high density region (Sample A.O. 1; ×50). FIG. 2—Typical vascular bundle from a low density region (Sample E.O. 3; ×60). FIG. 3—Thick-walled sclerenchyma fibres showing lamellated walls (Sample C.M. 1). The cracks are drying artifacts (×1000). FIG. 4—Thin-walled sclerenchyma fibres (Sample E.O. 3; ×650). FIG. 5—Thick-walled ground parenchyma cells (Sample B.M. 1). Note the thin-walled cells which occur sporadically throughout this tissue (×330). FIG. 6—Thick-walled ground parenchyma cells showing the lamellated structure of the cell walls and the intercellular pectic strands (×2200).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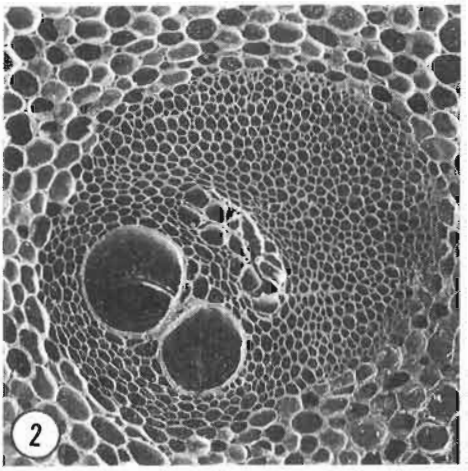
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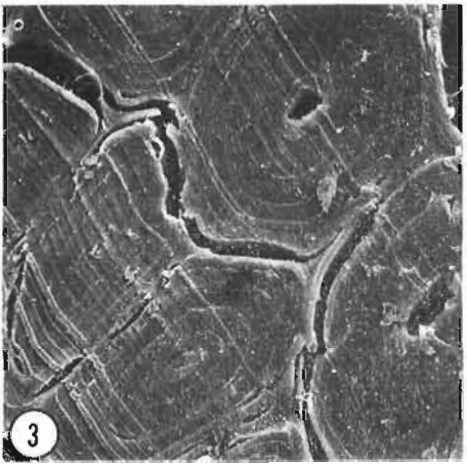
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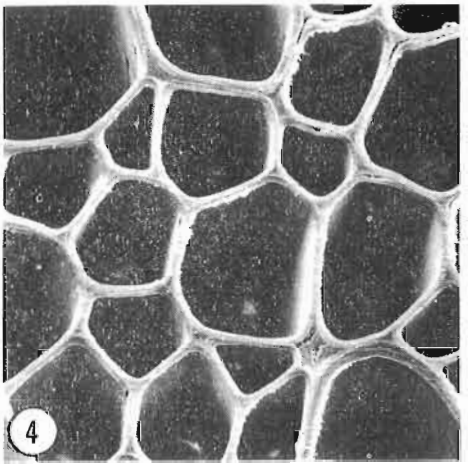
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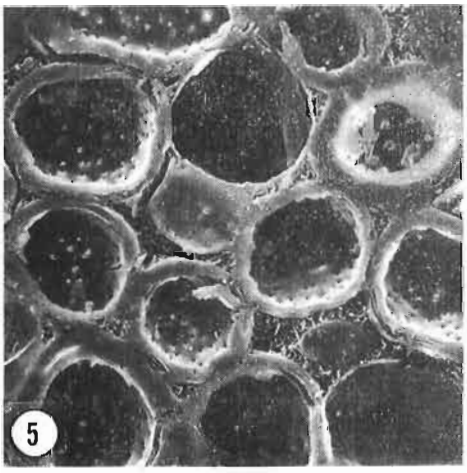
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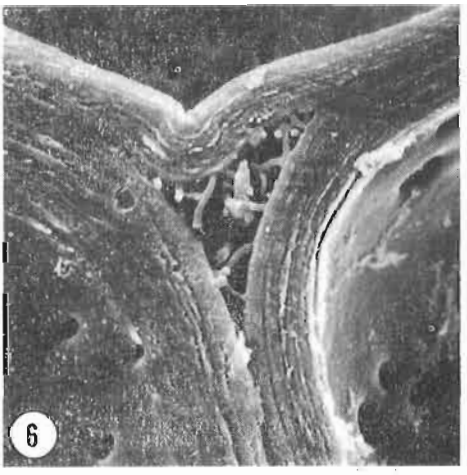
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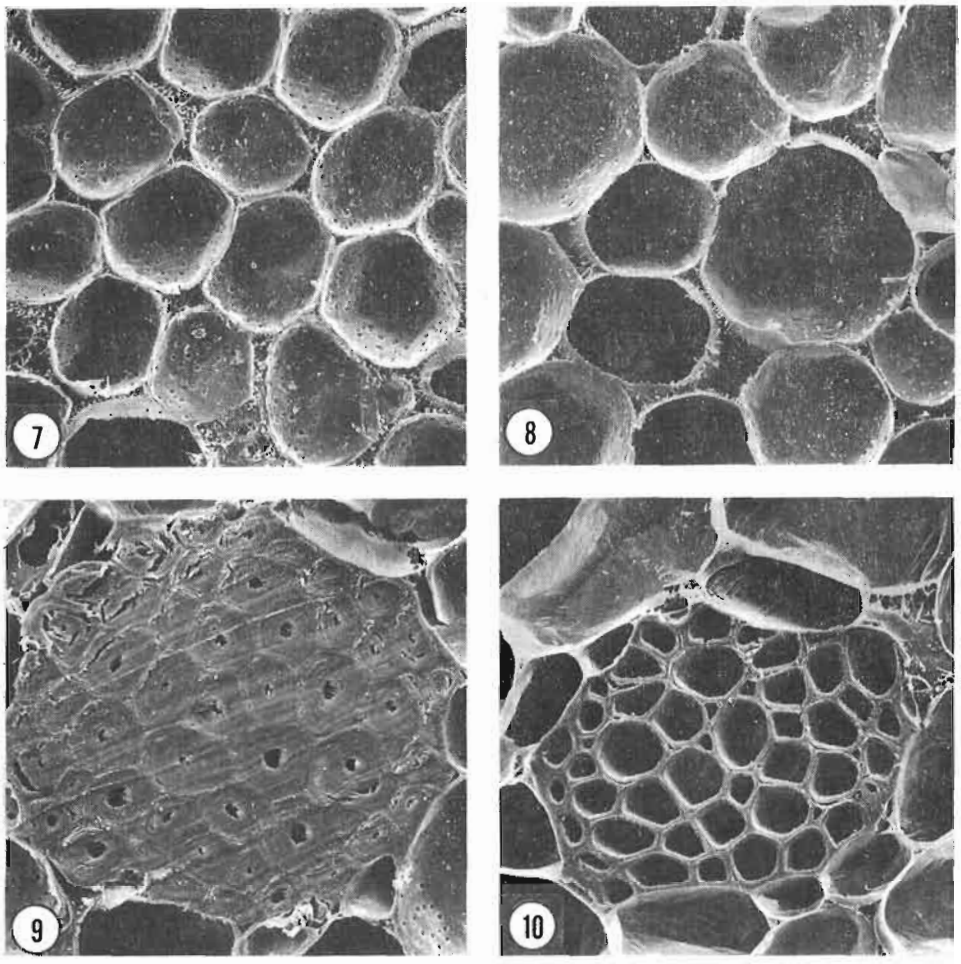

FIG. 7—Ground parenchyma cells (Sample C.O. 1; ×300). FIG. 8—Thin-walled ground parenchyma cells (Sample C.M. 3; ×300). FIG. 9—Fibrous strand (Sample A.M. 2) of thick-walled cells. The fibre walls are lamellated (×400). FIG.10—Fibrous strand (Sample C.Y.2) of thin-walled cells. Note the extremely thin-walled ground parenchyma cells probably unlignified (×400).

where they are absent or very rare. The wall thickness and number of lamellae in these fibres vary in a similar way to those of the sclerenchyma fibres in the local vascular bundles.

The general stem anatomy is closely similar to that of *Rhapis excelsa* as described by Zimmerman and Tomlinson (1965).

For a complete understanding of the anatomy it is necessary to consider the course and interconnections of the vascular bundles within the stem. These have been studied in great detail by Zimmerman and Tomlinson (1965, 1972) and Tomlinson and Zimmerman (1967) using a sophisticated micro cine-photography technique. In the present study it has been necessary only to consider changes in cell geometry occurring across transverse discs at several heights.

MATERIALS AND METHODS

A young (6.58 m high) a mature (11.28 m high) and an overmature (19.81 m high) palm all growing within a 9 m radius were selected at the Department of Forestry, Fiji. After felling, discs 2 cm thick were cut from each stem at heights of 0.91 m, 3.62 m, 6.28 m, 8.63 m, 10.97 m, 13.11 m, 15.24 m, 17.37 m and 19.51 m. Thus there were three discs from the young stem, five from the mature stem and nine from the overmature stem. From each disc a 2-cm wide strip, including the cortex and stem centre, was cut and immediately immersed in formalin-acetic acid-alcohol (F.A.A.) to preserve it from fungal attack and to keep it in the green condition. No more than 15 minutes elapsed between the start of felling and the time when the last strip was obtained. It will be seen later that storing the material in the green condition is important because some of it is prone to severe collapse. Samples of about 5-10 cm^3 in volume were cut out of each strip at three places: (1) from just beneath the cortex; (2) close to the stem centre; and (3) from about halfway between (1) and (2) (the 50% point). From the middle of each of these, a small strip about 8 mm square in transverse section and 2 cm long was cut and returned to F.A.A. until required for scanning electron microscopy and x-ray density determinations. The remainder of each sample was washed in distilled water and its basic density (dry weight divided by wet volume) determined. The number of vascular bundles per cm^2 of cross sectional area was also counted.

A transverse surface of each of the small strips was prepared by our usual method (Exley *et al.,* 1972; 1977). Critical point drying was used in all cases to minimise collapse. Even so, some shrinkage was unavoidable, and caused some wrinkling of the very thin walled parenchyma cells and splits in those vascular bundles having very thick walled fibres. The samples were examined in a Cambridge IIA scanning electron microscope.

To estimate the way in which density is affected by anatomy, it has been convenient to divide the stem into two classes of tissue according to cell wall thickness and also to estimate the void volume of the xylem and phloem. The main division has been between the thick walled sclerenchyma fibres of the vascular bundles and the remaining lower density material assumed to be ground parenchyma tissue. However with very low density tissue it has sometimes been more realistic to consider the axial parenchyma of the vascular bundles to be equivalent to fibres where their cell walls are of similar thickness and clearly different from the ground parenchyma cells.

The fibres can be considered to approximate to thick walled cylinders and so by measuring (1) the number of vascular bundles per cm^2; (2) the average area occupied by fibres in the bundles; and (3) the percentage cell wall material in an average fibre, the total volume of fibre wall per cm^3 of stem can be determined.

Initially the ground tissue was treated in a similar way but it became clear that the errors involved in measuring the wall thickness of very thin walled cells were considerable. In addition, there seemed no completely satisfactory way to estimate the intercellular void volume. Consequently it was decided to measure the amount of cell wall material in the ground tissue by x-ray densitometry.

A modification of the x-ray technique described by Hughes and de Alburquerque Sardinha (1975) was used. Transverse sections about 3 mm thick were cut from the same pieces as the SEM sections, washed in several changes of distilled water, taken

slowly through a graded alcohol series and dried by the critical point method. In this way collapse was avoided and the samples were closely similar to those prepared for SEM. The sections were then glued by their edges to small strips of wood with epoxy adhesive and assembled into slabs about 2 cm × 3 cm containing up to 16 sections.

Each slab was then accurately machined flat to a constant thickness of 2 mm. For calibration purposes a step wedge of cellulose acetate plastic and a strip of Douglas fir containing about 10 annual rings whose density profile had been measured by beta-ray densitometry, were used. The Douglas fir was machined to the same thickness as the coconut samples. Each slab together with the calibration strips was placed on a sheet of x-ray film and exposed to a source of soft x-rays (20 kV and 2 mA) at a distance of about 2 m. All the films were carefully developed together, with constant agitation, to ensure uniformity. The resolution was quite high and showed considerable detail of both vascular bundles and other tissue. The transmission of the processed film was measured using a scanning microdensitometer and the results were computer-processed to provide a numerical readout "map" of opacity every 0.25 mm^2. In most cases this procedure enabled us to discriminate easily not only against the fibre bundles but also against smaller regions of high density such as raphide crystals, other cell inclusions, and fibrous strands. In a few samples, however, the resolution was not adequate. These occurred mostly in the higher regions of the overmature stem where a considerable spread in the direction of the vascular bundles occurred and the number of crystalliferous cells was relatively high.

From the density measured in this way and the volume occupied by the ground parenchyma, the wall volume can be estimated. For this it is necessary to assume a value of specific gravity for the wall substance, here taken as 1.5.

RESULTS

Table 1 shows the sample labelling adopted (for example, the sample at 8·63 m in the mature stem at the 50% point is D.M. 2) and the distribution of basic density

TABLE 1—Distribution of basic density (kg/m^3) in coconut stem

Height	Y_1	M_1	0_1	Y_2	M_2	0_2	Y_3	M_3	0_3
J			249			147			100
H			539			184			109
G			511			140			110
F			430			176			117
E		232	424		145	153		83	115
D		315	419		141	106		112	105
C	178	823	422	82	350	143	83	188	124
B	279	883	635	121	609	334	86	373	136
A	298	721	647	150	243	238	89	139	184
Heights	A = 0.91 m		B = 3.62 m			C = 6.28 m			
	D = 8.36 m		E = 10.97 m			F = 13.11 m			
	G = 15.24 m		H = 17.37 m			J = 19.51 m			

Y refers to the young stem; M to the mature stem; O to the overmature stem; 1 to near the cortex; 2 to 50% of radius; and 3 to stem centre.

within the three stems. As a check on the accuracy of these values they are plotted in Fig. 11 against the saturated moisture content. The equation of the curve is

$$M.C.\% = \frac{9610}{D} - 67.45;$$ the correlation coefficient is 0.99.

This curve lies slightly below the theoretical one given by $M.C. = \frac{10\,000}{D} - 65.4$ (which assumes the specific gravity of the cell wall substance is 1.53).

It has sometimes been suggested that the specific gravity of "wood" substance in coconut may differ from the accepted value for wood. This curve is, however, fully compatible with a cell wall specific gravity of about 1.5; the small difference from the theoretical curve would be expected if complete saturation has not quite been achieved.

Table 2 shows the distribution at selected places within the stems of:

1. The number of vascular bundles per cm^2.
2. The area occupied by the thick walled sclerenchyma fibres in the vascular bundles.
3. The percentage wall material in an average fibre.
4. The density of the ground parenchyma tissue.
5. The relative areas of fibres, xylem and phloem lumen and ground parenchyma in the whole tissue.

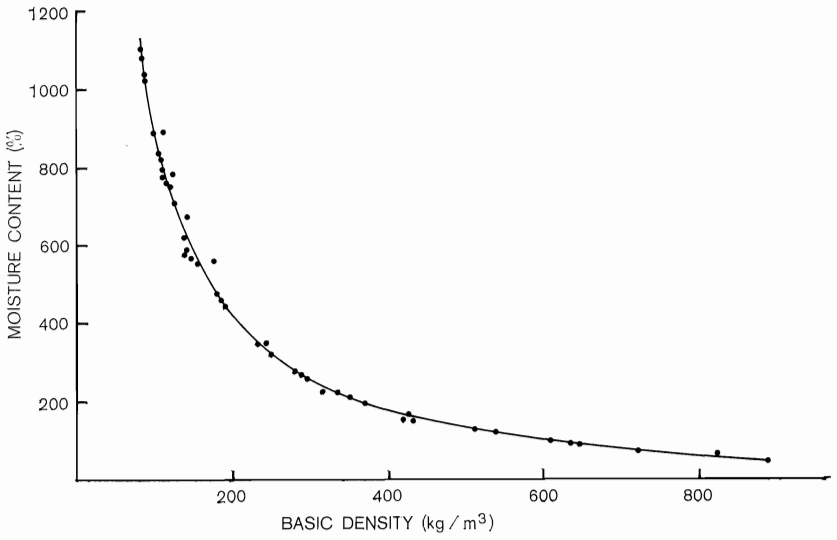

FIG. 11—Correlation between moisture content (based on oven-dry weight) and basic density.

The areas occupied by sclerenchyma fibres, ground parenchyma tissue and xylem lumen, and cell wall thickness vary widely both within and between stems but a general pattern emerges.

A. The number of vascular bundles per cm^2 decreases from cortex to stem centre at any height.
B. The number of vascular bundles per cm^2 increases with height at all relative positions across the stem. This probably reflects the reduction in stem diameter with increasing height (Richolson and Swarup, 1977).
C. The area occupied by fibres in the vascular bundles decreases from cortex to centre and with increasing stem height.
D. The fibre wall thickness decreases from cortex to centre.
E. The ground parenchyma wall thickness decreases from cortex to centre.
F. The lumen cross sectional area of the vessels in the vascular bundles increases from cortex to centre.

theless, as the main object has been to relate a particular anatomy to a particular density,

The accumulation of these factors leads to the very large changes in basic density (from 83 to 883 kg/m^3) observed within the stems of this species. Figures 1-10 illustrate some of the fibre and ground parenchyma cells encountered in this study. It is impractical to illustrate even a limited aspect of the anatomy of every sample. The intention is rather to show typical examples which can then be compared with the data of Table 2.

DISCUSSION

This work was initiated in part by the observation (A. S. Alston, pers. comm.) that basic density increases with age of the stem as well as decreasing with distance from the cortex and with height. In the three stems on which this investigation is based the variation of density pattern with age was not so clear cut. In particular, it was in the mature rather than the overmature stem where the greatest densities occurred. From the results of tests carried out at the Forest Research Institute, Rotorua, it would appear that our overmature palm is of lower average density than would be expected. Never- material from these three stems has been very useful experimental material.

From Table 3 the total volume of cell wall material in unit volume of the whole tissue can be calculated. In Fig. 12 this is plotted against the basic density.

In plotting this relationship a correction of 5% has been made in the number of vascular bundles to allow for the shrinkage occurring between the saturated condition when that was determined and the vacuum-dry condition when the fibre areas were measured.

The high coefficient of correlation suggests that most of the variation in density can be explained in terms of changes in cell wall thickness and the relative proportions of the two types of cells.

No allowance has been made for the presence of the small fibrous strands or inclusions such as crystals and other deposits. These fibrous strands are much more common in the central lower density regions of the stem and together with the inclusions

TABLE 2 (opposite) — Values marked * were for samples with thin fibre walls where it proved difficult to define the fibre area precisely. Values given include the axial parenchyma.

Sample	Number of vascular bundles /cm²	Average cross-sectional area of fibres (cm²)	Fibre wall %	Ground Tissue Density kg/m³	Relative proportions of:		
					Fibres	Xylem Phloem Lumen	& Ground parenchyma
AY1	44	0.008 0	47	100	0.35	0.01	0.64
AY2	18	0.007 7	38.5	45	0.14	0.01	0.85
AY3	6	0.004 5	30.5	36	0.03	0.005	0.97
BY1	71	0.006 5	42	130	0.47	0.02	0.51
BY2	25	0.005 8	38	36	0.15	0.03	0.82
BY3	16	0.004 1	30	45	0.07	0.01	0.92
CY1	78	0.004 9	20	63	0.38	0.03	0.59
CY2	23	0.003 9	15	23	0.09	0.03	0.88
CY3	23	0.003 7	16	23	0.09	0.04	0.87
AM1	51	0.009 0	90	225	0.46	0.01	0.53
AM2	16	0.005 2	90	77	0.08	0.01	0.91
AM3	9	0.003 5	80	54	0.03	0.005	0.97
BM1	91	0.007 7	90	594	0.70	0.03	0.27
BM2	36	0.004 3	90	378	0.16	0.03	0.81
BM3	23	0.002 9	90	180	0.07	0.01	0.92
CM1	93	0.005 4	90	387	0.50	0.03	0.47
CM2	50	0.003 6	72	90	0.18	0.05	0.77
CM3	21	0.003 7	60	63	0.08	0.02	0.90
DM1	108	0.004 3	31	108	0.46	0.03	0.51
DM2	54	0.003 3	27	50	0.18	0.06	0.76
DM3	34	0.004 5*	21	54	0.15*	0.06	0.79
EM1	146	0.003 2	24	—	0.47	0.05	0.48
EM2	86	0.002 4	20	55	0.21	0.67	0.73
EM3	36	0.005 2*	18	54	0.19*	0.09	0.73
AO1	60	0.008 0	90	266	0.48	0.02	0.50
AO2	28	0.006 7	85	68	0.19	0.03	0.78
AO3	19	0.004 3	80	68	0.08	0.03	0.88
BO1	71	0.005 4	90	185	0.38	0.03	0.59
BO2	42	0.004 9	80	100	—	—	—
BO3	17	0.004 8*	15	58	0.08*	0.02	0.90
CO1	93	0.005 0	58	167	0.47	0.05	0.48
CO2	22	0.008 8*	13	54	—	—	—
CO3	18	0.004 2*	13	59	0.08*	0.04	0.88
DO1	97	0.004 3	70	148	0.42	0.06	0.52
DO2	27	0.006 9*	17.5	55	0.19	0.04	0.77
DO3	23	0.007 4*	17.5	50	0.17	0.03	0.80
EO1	116	0.003 3	80	153	0.38	0.03	0.59
EO2	39	0.001 5	27	95	0.06	0.04	0.90
EO3	22	0.001 5	17	65	0.03	0.02	0.95
FO1	116	0.003 0	75	151	0.35	0.03	0.62
FO2	58	0.002 3	21	103	0.13	0.05	0.82
FO3	39	0.005 0*	15	70	0.20*	0.06	0.74
GO1	162	0.001 8	85	221	0.29	0.05	0.66
GO2	65	0.006 5*	20	99	0.42*	0.08	0.50
GO3	54	0.001 9*	32	59	0.10*	0.04	0.86
HO1	199	0.001 5	90	310	0.30	0.08	0.62
HO2	117	0.001 9	15	—	0.22	0.09	0.69
HO3	58	0.003 2*	18	—	0.19*	0.05	0.76
JO1	175	0.002 3	26	—	0.40	0.04	0.56
JO2	103	—	28	—	—	—	—
JO3	68	—	25	—	0.17	0.09	0.74

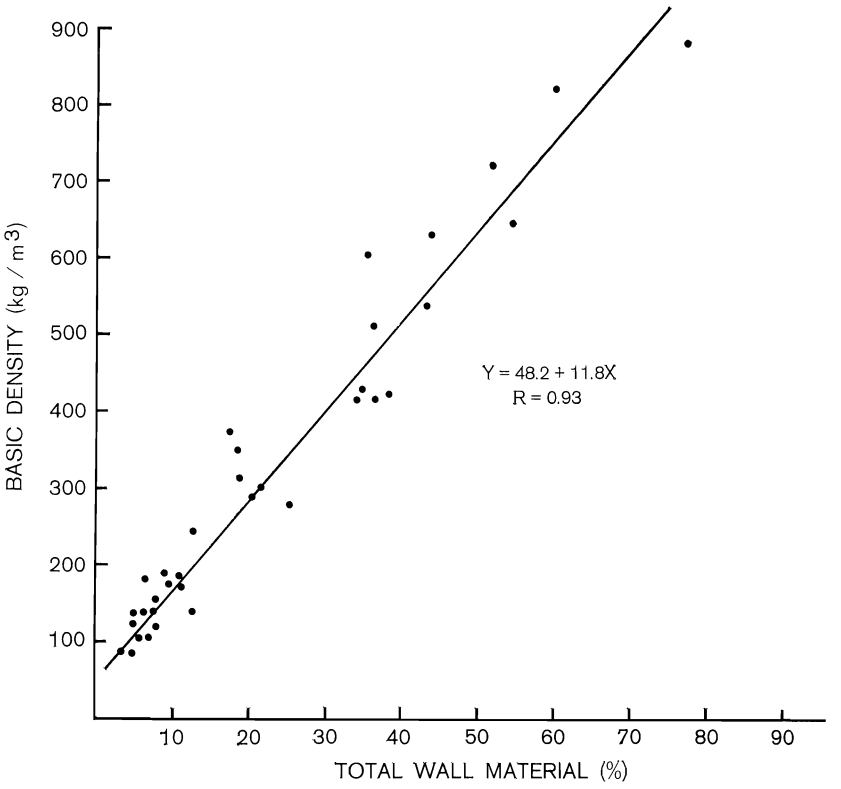

FIG. 12—Correlation between basic density (Y) and total amount of cell wall material (X).

may well account for the intercept on the basic density axis. In some of the lower density samples for example the inclusion of the fibrous strands would increase the apparent ground parenchyma cell wall volume by about 20%.

The accuracy of any individual measurement is unlikely to be very great; nevertheless, the correlation between basic density and estimated cell wall volume is very high. The relationship of Fig. 12 may suggest that the specific gravity of coconut stem cell wall material is about 1.2 rather than the accepted value of about 1.5 for wood. This is most unlikely and the apparent discrepancy is almost certainly due to an overestimate of fibre wall thickness. This is a well known phenomenon in optical measurements of cell wall thickness. For example, the specific gravity of softwood cell walls based on such measurements is underestimated by about 30% (Harris, 1969).

Several attempts have been made to relate basic density to the number of vascular bundles per unit area. Kloot (1952) using New Guinea material found a high correlation between these parameters but remarks that this might be more apparent than real because no account was taken of the density of the individual vascular bundles. Richolson and Swarup (1977) on the other hand using Fijian material found a correlation coefficient of about 0·5 (based on 24 measurements) and a significantly different regression equation. Figure 13 shows the regressions of both Kloot and Richolson

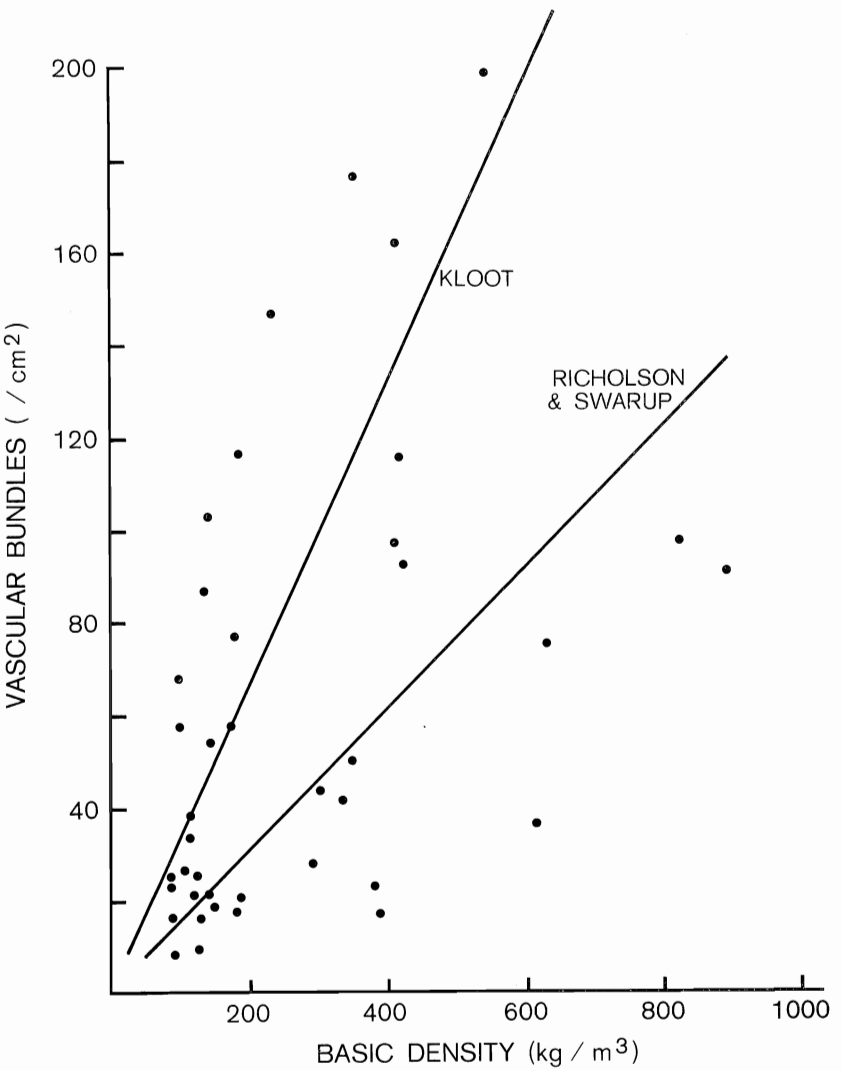

FIG. 13—Correlation between the number of vascular bundles per cm^2 and basic density (after Kloot, 1952; Richolson and Swarup, 1977).

and Swarup with the data from the present survey, which has a correlation coefficient of only 0.18, overplotted. On the other hand the correlation between the amount of fibre wall material per unit volume and basic density, shown in Fig. 14, has a correlation coefficient of 0.88. Longitudinal strength properties are likely to be largely dependent on the sclerenchyma fibres and this observation supports that of Orman (1974) who found high correlations between strength properties and density.

Figure 15 shows the relationship between the density of the ground parenchyma alone (corrected to zero moisture content) and basic density of the whole sample. The correlation coefficient is 0.62.

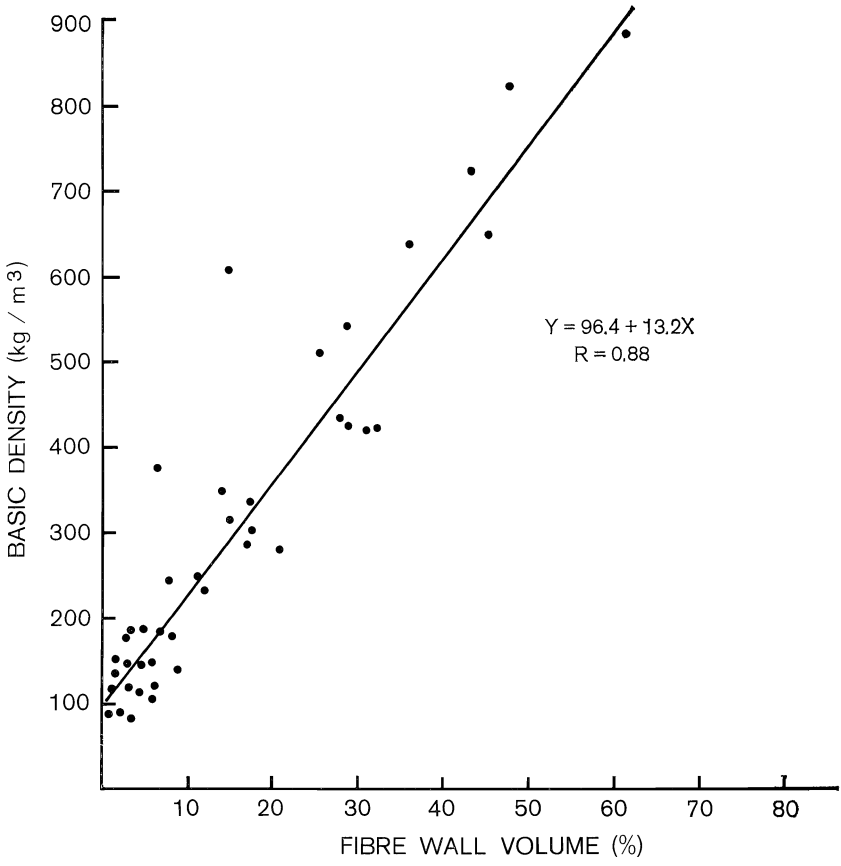

FIG. 14—Correlation between basic density (Y) and sclerenchyma fibre wall volume (X).

It can be seen that while basic density is affected mostly by the sclerenchyma fibres there are some samples where the relative contribution of the ground parenchyma is much greater than elsewhere. Thus similar basic densities can be due to quite different proportions of sclerenchyma fibres and ground parenchyma. Such a situation may perhaps occur in palms of different varieties or from different climatic sites. In these circumstances a different relationship between some properties, such as tensile strength, and density, might be expected.

No studies appear to have been made of the fine structure of the fibre walls in *Cocos nucifera* but they are very similar in appearance to those found in bamboo which have alternating broad and narrow lamellae (Parameswaran and Liese, 1976). There the broad lamellae have microfibrils orientated at a steep angle (2-20°) to the cell axis and the narrow lamellae have microfibrils orientated almost perpendicular to the cell axis. The few measurements on the thick walled *Cocos nucifera* fibres (Cousins and Meylan, 1973) indicated a microfibril angle of less than 10°.

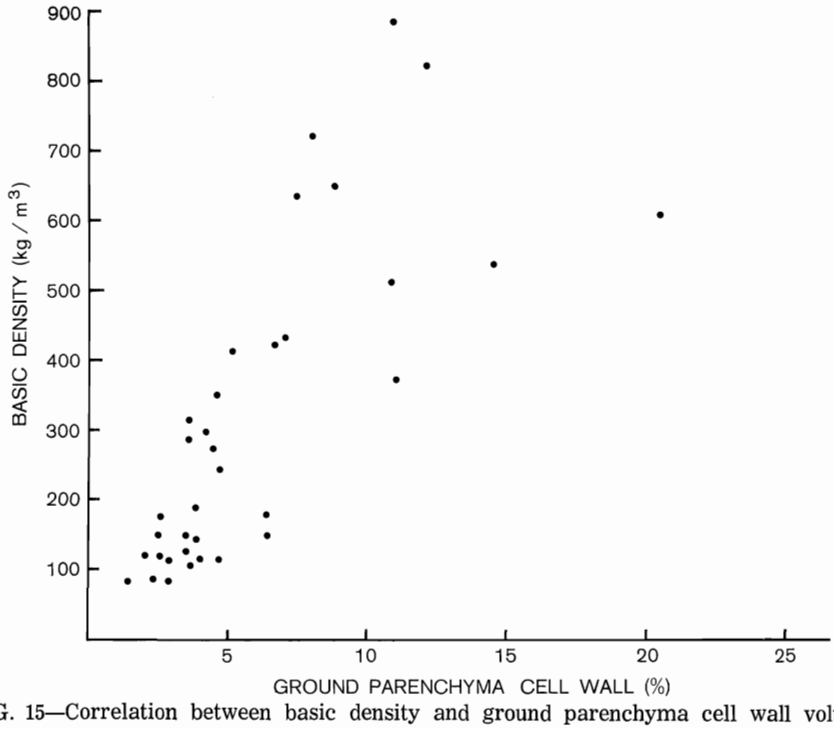

FIG. 15—Correlation between basic density and ground parenchyma cell wall volume.

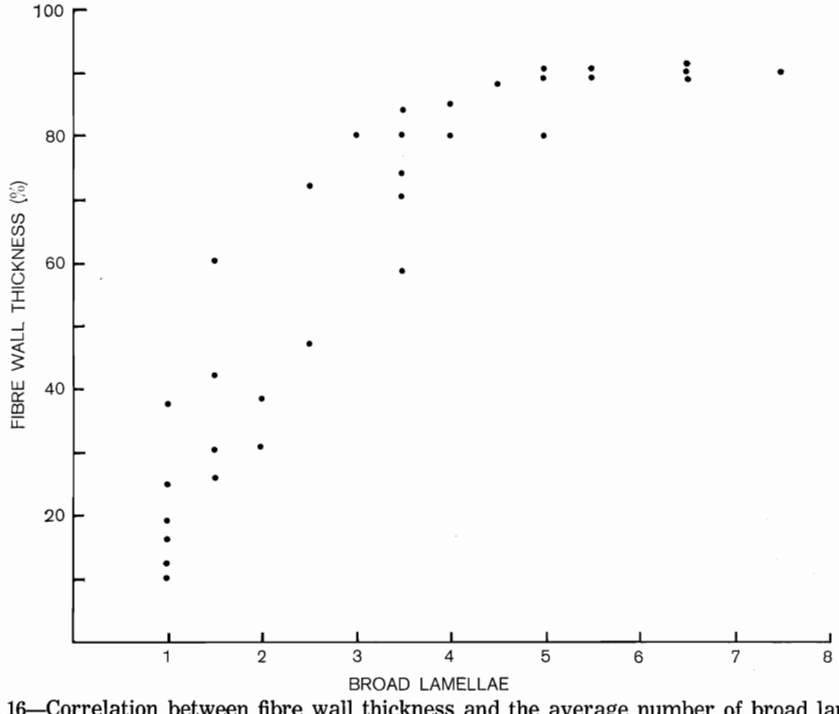

FIG. 16—Correlation between fibre wall thickness and the average number of broad lamellae for fibre.

The number of lamellae in the fibre wall appears to be closely related to total wall thickness (Fig. 16). The regression, % fibre wall = 20.4 + 40.6 log N (where N is the number of lamellae) has a correlation coefficient of 0.91. The logarithmic form has no significance apart from mathematical convenience. There are a large number of vascular bundles having single layered fibres and data from only a few of these have been included on the graph. Within a single vascular bundle both the wall thickness and number of lamellae often vary widely. In these cases an average value for both has been taken.

The ground tissue parenchyma cells that have thick walls also have a lamellated structure (Fig. 16). The lamellae are relatively thin and it was not possible to determine the way in which the number varied with wall thickness.

CONCLUSIONS

The wide range of density observed in *Cocos nucifera* is, as might be expected, a result of changes in cell wall thickness. Complications arise because the "wood" is structurally a two phase system of thick walled sclerenchyma fibres embedded in ground parenchyma tissue, both of which vary in cell wall thickness independently in a progressive way with distance from the cortex and with height. There is also an age variation which occurs, because the cells continue to live for a very long time, at all positions in the stem. During this time the sclerenchyma fibres and ground tissue may continue to lay down secondary wall material. This is reasonably clear in the two younger stems but in the overmature stem the evidence is inconclusive. As this stem is possibly atypical, the effect of age on cell wall thickness needs further study based on material from a larger number of stems.

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