



Frontispiece: A plantation of *Eucalyptus deglupta* at Keravat, New Britain.
Age: 15 years, mean tree diameter at breast height: 43.2 cm, mean tree
height: 47.3 m.

**VARIATION, ASSOCIATION AND
INHERITANCE OF MORPHOLOGICAL
AND WOOD CHARACTERS IN AN
IMPROVEMENT PROGRAMME FOR
EUCALYPTUS DEGLUPTA BLUME**

by

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THIS THESIS WAS SUBMITTED IN
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A handwritten signature in cursive script, appearing to read 'J. Davidson', written in dark ink.

J. Davidson

Canberra, A.C.T.

March 1972

ABSTRACT

DAVIDSON, J. (1972) Variation, association and inheritance of morphological and wood characters in an improvement programme for *Eucalyptus deglupta* Blume. Ph.D. Thesis, Australian National University, Canberra, Australia.

Up to 93 percent of variation in the wood of 20-year-old *Eucalyptus deglupta* Bl. has been explained by four components of a principal components analysis. Fibre cross-sectional characters were the main parameters contributing to this variation. Density satisfactorily represented the main and one subsidiary component which, together, represented 70 per cent of the total variation. Density was easy to measure and had a phenotypic variation of about 20 per cent of the mean value. It had a broad sense heritability of 0.68 ± 0.17 and a narrow sense heritability of 0.44 ± 0.23 in seedling material. Density could be modified irrespective of growth rate and stem form in trees 14-20 years old. Hence wood density is a very suitable factor for including in a tree improvement programme.

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CHAPTER 1

INTRODUCTION

Plantation forestry, in its relatively long rotation form, is becoming less attractive as an investment opportunity because of rising interest rates and the long term investment required. The future need is for large areas of quick-growing plantations producing adequate returns after rotations of less than eight to ten years. The main aim of industrial forest management must be to obtain, from these short rotations, the highest nett value of final products for a given investment, i.e., the greatest rate of return. This goal is obtainable firstly by achieving the highest biological production in useable form and secondly by greatest recovery of processed products, consistent with the need to maintain high profitability. Achievement of increased biological production from a species requires identification of genetic and environmental components of production followed by quantification and manipulation of those components to achieve the desired end. Highest recovery of useful and profitable products involves the type and quality of the wood. This can be related to, but need not necessarily be compatible with, the maximum biological production aim.

Forestry and the wood using industries are demanding more exact and detailed information on wood properties, particularly those properties that have become, or are expected to become, of importance in processing or in the suitability of the manufactured products for various end uses. It has been demonstrated that industry can make great technological advances in developing techniques to handle

certain categories of raw material (e.g., there is increasing use of woods with short fibres for pulps). The main goal of management, in the future, should be to provide a maximum quantity of wood which is as uniform as possible to cater for the trend towards greater use of reconstituted wood. If uniformity is obtained, and a large quantity of this wood is available from short rotation plantations, industry will adapt itself to it. Moreover, many of the desirable features of wood raw material for reconstituted products also enhance its usefulness in more traditional uses such as sawn timber.

The main criterion of production in forestry has nearly always been the volume of wood produced. This has led to many problems, as volume is not a true measure of the amount of wood fibre or cellulose produced. The weight, and in particular dry weight, is a more reliable criterion. In order to use weight as an estimate of production, detailed knowledge of the density of wood and the factors determining it are required.

In Papua and New Guinea, an area of special interest to the author, *Eucalyptus deglupta* Blume is a species suitable for short rotations. This species has been grown in trial plantations in Papua and New Guinea at several locations within its natural range. Since 1948, more than 1,000 acres (405 hectares) have been established at Keravat, New Britain. The species has exhibited outstanding growth and many desirable attributes (Chapter 2). Eucalypt species have been successfully introduced into many parts of the world, especially in warm temperate and tropical areas where growth and volume production has frequently exceeded that of the forest they replaced (Pryor, 1967). It is evident that *E. deglupta* could find wide-spread use in tropical and subtropical lowland areas as

growth of *E. deglupta* grown in trial plots, as an exotic, in many countries has been very promising.

A tree improvement programme was initiated with this species by the author in 1966, in order to provide desirable seed for large scale plantations. This thesis describes aspects of this programme including the variation of wood properties within and between trees, provenance variation, genetic and environmental variation, heritability and tree selection methods.

An effective tree breeding programme requires a synthesis of many factors: an intimate knowledge of the species, and of the environments and their interaction, a flexible breeding strategy capable of being modified or diversified at a later date to follow new trends in utilization, and an interaction with non-genetic means of tree improvement such as soil fertilization. As much variation as possible must be maintained during initial research and development of desirable trees to provide material for any possible breeding option. The aim is to develop reservoirs of breeding material from which one can satisfy at least some of the demands of industry in the future. However, the time scale in forestry, even with a fast growing tropical species, does impose an inescapable need to attempt to predict future requirements qualitatively and quantitatively at an early stage. For a particular option, the reservoir of breeding stock must be able to provide uniformity in wood quality for the required end use.

Little information has been published on *E. deglupta*. An intensive campaign of collection and collation of information was instigated to improve general knowledge of the species, its distribution and ecology. An introduction to the species is given in Chapter 2.

The properties of wood as a raw material for industry are determined basically at a cellular level. At this level, both chemical and physical variations may be important. At a higher level, variability in anatomy gives rise to anisotropy in wood. This variability extends to all levels within and between trees of the one species. Features of interest therefore include cell dimensions, the relative proportions and arrangement of different tissue elements and chemical composition. Although it is recognized that cell ultrastructure could have a bearing on the performance of wood as a raw material, this aspect was considered beyond the scope of this study. Variation of a number of characters within small samples of wood and its effect on obtaining statistically reliable measurements of various parameters is described in Chapter 3. Cell micrographic characters and their many ratios, proportions of tissue types, dilute alkali soluble extractives and sulphuric acid soluble lignin were considered the more important parameters to be studied in detail in the time available.

Many of these parameters are difficult and tedious to measure precisely. For many years, wood density has been accepted as an easily measured, significant, quantitative feature of particular importance because so many factors of yield and quality of end products are associated with it. It would be desirable in the breeding programme to use density as a criterion to replace some or all of the many important parameters discussed. However, density is not a simple character in the biological sense. In eucalypts, it results from a complex tissue structure and cell characteristics probably themselves determined by a complex physiological system. If we also consider possible effects of

extractives and remember that wood volume changes in the presence of moisture, density becomes a very complex parameter indeed.

If density is a direct measure of the weight of wood produced and, at the same time, relates to many wood properties, it could characterize the production and uniformity variables for the improvement programme. Thus, one of the preliminary goals was to establish the reliability of density as a criterion for the breeding programme and to determine its relations with other properties.

Zobel (1964) stated:

"It is obvious that the maximum efficiency in breeding for specific gravity (density*) cannot be achieved until it is known how to control the components determining it".

The measurement of density by gravimetric and radiation methods is discussed in Chapter 5. The relationship between density and the other measured parameters was investigated and important correlations were determined (Chapter 6). Statistical techniques not previously attempted in wood quality studies were used to isolate the main parameters of the density complex.

Within tree variation of wood properties was investigated to overcome problems associated with representative sample selection and enable a single sample to characterize individual mature trees and seedlings (Chapter 7).

*Author's brackets: the terms density, basic density and specific gravity have been considered synonymous in this study to simplify problems of nomenclature. See Chapter 5.

The practical aspects of the tree improvement programme were considered on the basis of these preliminary but very necessary investigations. Any programme which fails to examine the total gene pool available for selection would almost certainly be ignoring a potentially important source of breeding material. Many studies of geographic variation with other species have indicated that important differences may exist between properties of a particular species originating in separate areas. Provenance studies indicate that some species contain geographic races which may produce different phenotypes when grown under similar conditions. Several provenances of *E. deglupta* were grown under controlled environments in a phytotron while parallel field trials were established in several tropical areas. Results of these studies are presented in Chapter 9.

Richardson (1962) has stressed the need for physiological contributions to the study of factors modifying anatomical features through elucidation of the controlling processes. Part of the intraspecific anatomical variation may be controlled genetically (e.g., Dadswell *et al.*, 1959, 1961; Echols, 1955; Kennedy *et al.* 1954; Rees *et al.* 1954; Zobel, 1956) and many attempts to select or breed strains of tree species with desirable wood properties are prominent in the literature (e.g., Dadswell, 1958; Dadswell *et al.*, 1959; Echols, 1955; Fielding *et al.*, 1960; Jackson *et al.*, 1958; Schreiner, 1958; Zobel *et al.*, 1957, 1962). However, wood properties are also markedly affected by environment (e.g., Dinwoodie, 1961; Larson, 1962) and the significance of this must be evaluated satisfactorily. Detailed studies of environmental effects on the growth of this species are outside the scope of the present investigation. However, it was desirable to explore the

variation between individuals of the one provenance growing in controlled environments to gain some basic knowledge from which to develop and judge the effectiveness of several breeding systems available (Chapter 10).

It is essential to know how morphological characters and wood properties are transmitted from parent to progeny. Qualitative descriptions of inheritance are far from adequate for this purpose and information must be presented more precisely by some measure of the intensity of genetic control accompanied by a measure of the standard error of the estimate. The most commonly used measure of genetic control is a ratio called 'heritability', applied in either a broad or narrow sense. Heritability is not an absolute property of a species but a single statistical result of a properly designed experiment carried out under fully and clearly stated conditions. Zobel (1964) has stated that few studies have explicitly described the type of population, the kind of environment and the time interval used for the experiment. Components were examined in numbers large enough for an estimate of their variances to be meaningful and confidence limits to be ascertained (Chapter 11). Without these deliberations later reliable prediction of genetic gain would be impossible.

Any tree breeding programme must consider attempts to improve, in relation to industrial requirements, many features, including growth rate, tree form, wood anatomy and wood chemistry. These may vary either dependently or independently with each other. The geometrical progression arising from multiple factor selection is all too familiar having been stressed and illustrated repeatedly in the literature. A two stage selection programme has been adopted; the first stage involving selection for tree form and vigour in the

field and the second stage involving selection for desirable wood properties. Some system of ranking or order of priority to be applied to individual tree characteristics is needed. The selection and ranking of characteristics are to a great extent dictated by management and policy decisions as a result of industrial (and perhaps political) requirements. Selection criteria from the viewpoint of the particular requirements of Papua and New Guinea, which already has a sizeable area of plantation grown *E. deglupta*, are discussed in Chapter 12.

In summary, the main aims of the experimental work were:

- I. To explore the variation of a number of important parameters in *E. deglupta* wood within small samples (1 cc in volume) and determine how this variation could be used to derive sample average values.
- II. To use sample average values to determine the degree of association between the measured parameters.
- III. To try and characterize the small samples by use of only a few of the measured parameters and to relate as many as possible to density, a complex variable.
- IV. To determine within tree variation and how the wood of individual trees could be characterized by a single representative sample.
- V. To use representative sampling to investigate variation in wood properties between trees, and between geographic areas.
- VI. To determine the relative importance of genotype and environment as causes of observed variation in wood and morphological characters by imposing a number of different environmental treatments on seedlings and young clonal material.

- vii. To use the genetic information obtained to determine which characters would be of value in selection of desirable trees in a tree improvement programme.
- viii. To determine phenotypic correlations between characters used in selection.

Gaps exist in our knowledge of many of these aspects, especially in regard to eucalypts. Many early studies in the genus were limited to few samples and the results were not adequate for detailed statistical analyses.

The interdependence and practical significance of these studies has been illustrated by presenting them within the framework of a tree improvement programme. The work and results are generally applicable to any fast growing eucalypt.

CHAPTER 2

EUCALYPTUS DEGLUPTA - AN INTRODUCTION TO THE SPECIES

2.1 INTRODUCTION

In this Chapter some notes are presented to familiarize the reader with the species, its ecology and distribution. An up-to-date account of general knowledge of the species will be published separately.

2.2 TAXONOMY

The following account of the history of the species is taken from Maiden (1903-1933), except where otherwise indicated.

The type specimen was collected by Reinwardt in the mountain forests of the Celebes in 1821. This sterile specimen was given the manuscript name of *Populus deglubata* by Reinwardt. In 1849, Blume recognised that the specimen was not a poplar and belonged in *Eucalyptus*. He used it to describe *Eucalyptus deglupta*.

A further specimen, this time in fruit, was collected, presumably by Rich, at Caldera, Mindanao during the course of an expedition (1838-1842) by Charles Wilkes, U.S.N. This material was described as *Eucalyptus multiflora*.

Mueller (1886) received sterile material from New Britain which he used to describe *Eucalyptus naudiniana*.

As no buds had been seen by the first three authors mentioned, there remained some doubt whether the species described were attributable to *Eucalyptus*.

Maiden obtained material in flower and bud and was able to show that the species was correctly placed in *Eucalyptus*. He also showed that the Philippines material (*E. multiflora* (Rich) A. Gray) and that from New Guinea (*E. naudiniana* F. Muell.) were of the same species. He declared *E. multiflora* to be invalid as the name was pre-occupied ('*E. multiflora* Polret, probably a synonym of *E. pilularis* Smith') and *E. naudiniana* F. Muell. was the correct one.

Meanwhile in 1908-1909, Schlechter had collected specimens from Jaduna on the Waria River (New Guinea). One of these was used by Diels (1922) to describe the type *Eucalyptus schlechteri*. Bark, timber, juvenile leaves and anthers were not described.

Merill (1923) showed that *E. naudiniana* was a synonym for *E. deglupta*. Blakely (1934) accepted this finding but, as neither he nor Maiden had seen material of *E. schlechteri*, this was maintained as a separate species. Blake (1953) stated, without giving evidence, that *E. schlechteri* must be considered as conspecific with *E. deglupta*.

Johnston and Marryatt (1965) are in error in stating that *E. deglupta* was 'formerly *E. naudiniana* F. Muell.' as no name change was involved. However, they accept that *E. deglupta* should include *E. schlechteri*.

The confusion associated with this species was largely due to the inadequacy and variability of the early material collected and to lack of communication between herbaria. More recent collections made throughout the range of the species confirm that the previously described separate species fall within the rather wide range of variability shown by *E. deglupta*.

2.3 SYSTEMATIC POSITION

Maiden (1910) pointed out that it is not easy to establish the affinities of this species. The anthers are anomalous in that, although the shape is renantherous, the lobes dehisce by separate slits.

However, Blakely (1934) placed *E. deglupta* and *E. schlechteri* with *E. raveretiana* F. Muell. and *E. brachyandra* F. Muell. in series Myrtiformes of section Renantherae.

Blake (1953) stated that *E. deglupta* seems to be only loosely allied to Australian species of *Eucalyptus*.

Gaub and Pryor (1958) have described a testa structure different from that of the Renantherae. Carr and Carr (1959) found the operculum structure also not to be the same as that of the Renantherae.

Pryor and Johnson (1971) include *E. deglupta* in subgenus Symphomyrtus, section Equatoria, series Degluptae with *E. raveretiana* and *E. brachyandra*.

2.4 COMMON NAMES

In Papua and New Guinea, the common and trade name for *E. deglupta* is kamarere. Other important common names are leda in Indonesia and bagras in the Philippines.

2.5 NATURAL DISTRIBUTION

Accurate information on the natural distribution of *E. deglupta* has been slow to accumulate. Modern ground and air survey techniques have enabled many stands to be mapped, especially on New Britain where the first assessments were carried out by the Army (Australian Military Forces, 1945). The species is easy to identify from the air and from air photographs (Plate 2.1).

There are several riverine stands in Mindanao, although many are being destroyed by agricultural activity. *E. deglupta* occurs extensively in the Celebes and occurs also in Ceram (Moluccas) (Ferguson, 1949, 1950).

The West Irian distribution is supported by only three collections, one from Mount Nettotl and two from Panlai Lake, near Kebo.

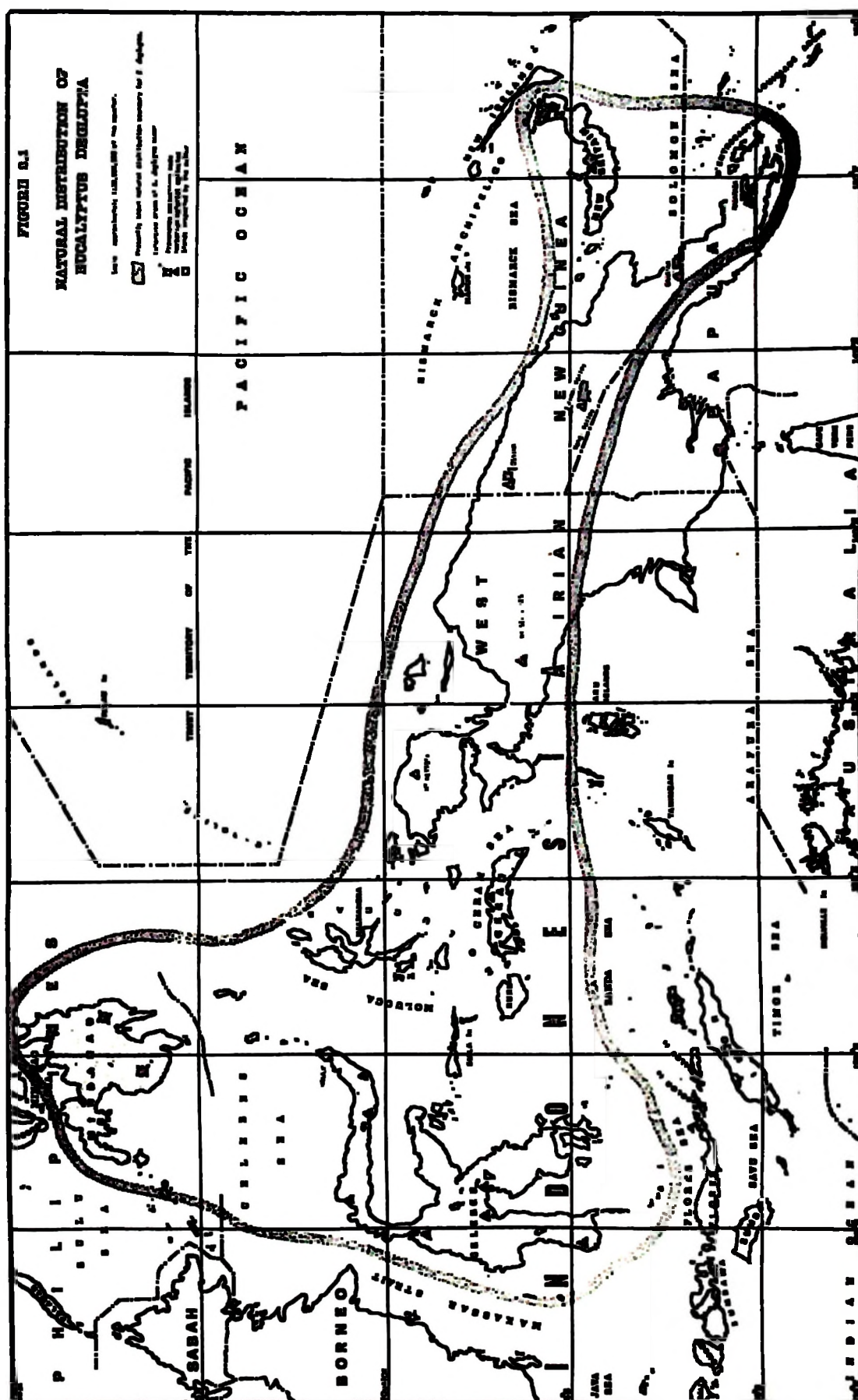
The author has inspected and confirmed the distribution in north-west New Guinea. Information is lacking to support a continued distribution from Ossima in New Guinea westwards to Mount Nettotl in West Irian.

Another apparently discontinuous area of *E. deglupta* occurs in the New Guinea Highlands District. It has been reported and collected from the Chimbu, Wahgi and Jimmi River Valleys.

In south east Papua and New Guinea, many collections have been made north of the main dividing range. This distribution is very well established. Scattered stands of *E. deglupta* are to be found also on the Papuan south coast.



PLATE 2.1 Vertical air photograph showing stands of *E. deglupta* (arrowed) along the Torlu River. Scale: approximately 1 inch (2.5 cms) = 1 mile (1.6k).



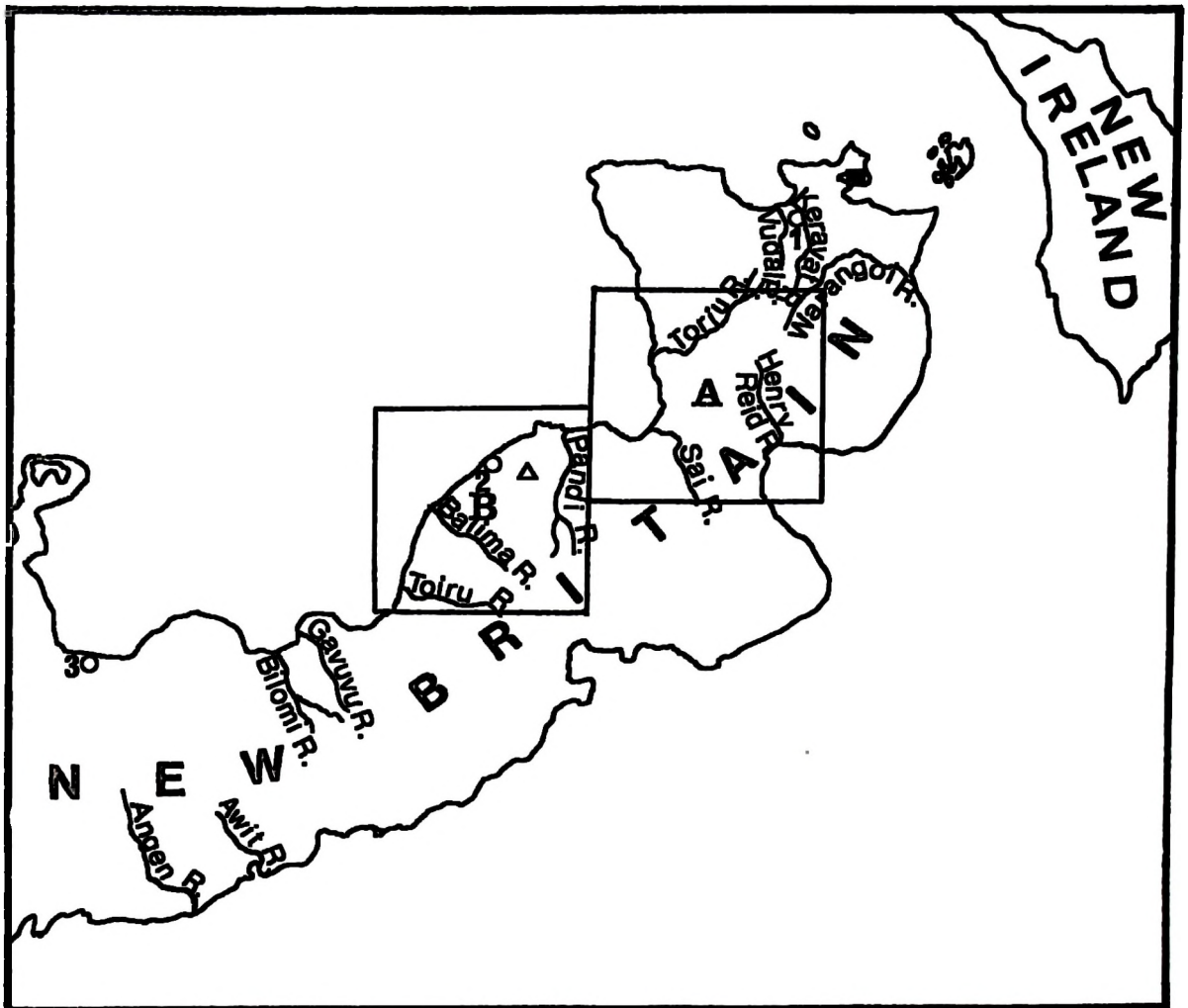


FIGURE 2.2 Map of New Britain showing the location of some of the main rivers on which *E. deglupta* occurs. For a general location see map on page 15. The areas delineated "A" and "B" are shown in more detail in Figures 2.4 and 2.5 respectively. ■ Rabaul ○ Towns: 1. Keravat, 2. Ulamona, 3. Hoskins. Δ Mt. Ulawun (The Father).

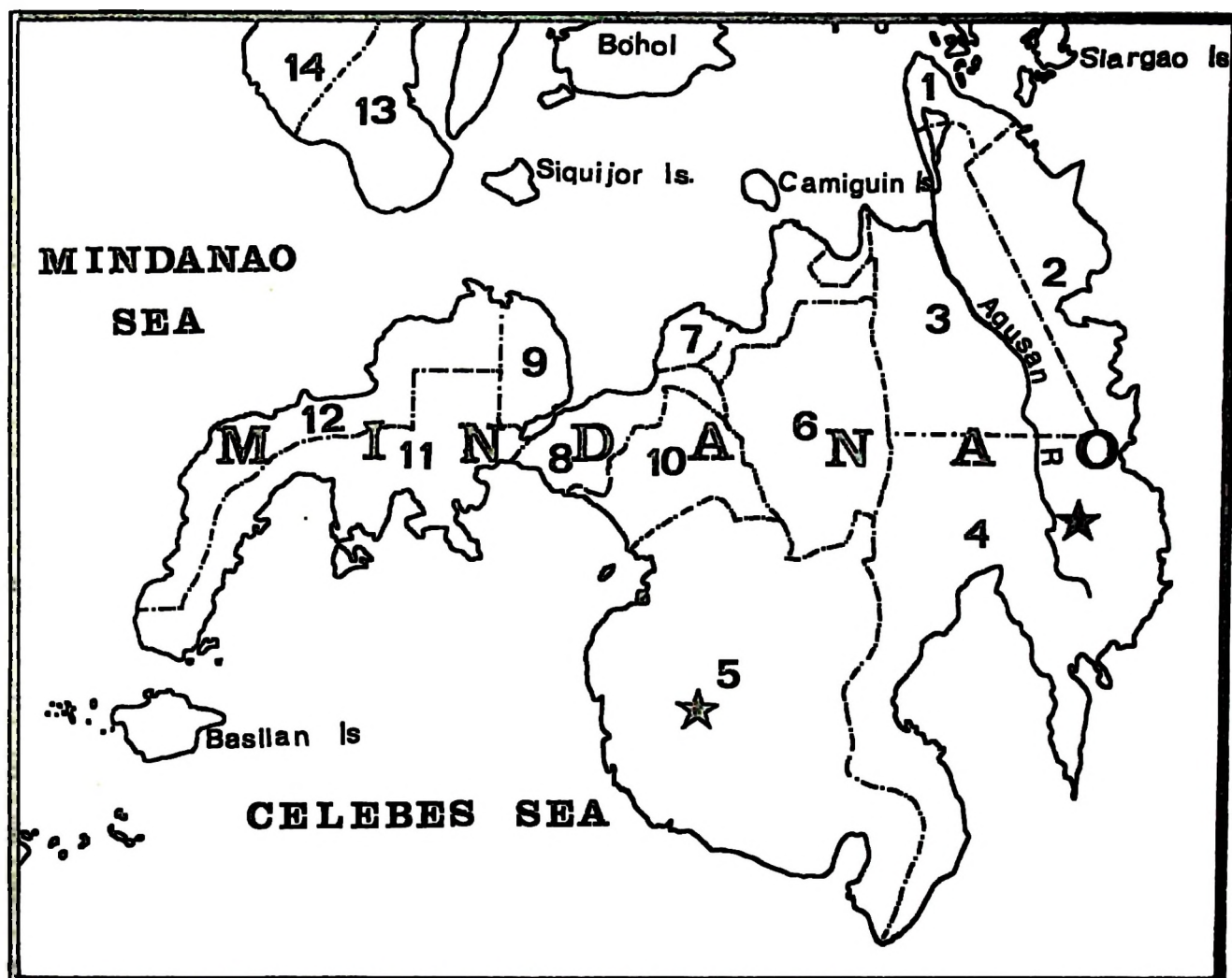


FIGURE 2.3 Map of Mindanao, showing the location of the Agusan River along which are many stands of *E. deglupta*. For a general location see map on page 15. Provinces of Mindanao and islands to the north are: 1 Surigao del Norte; 2 Surigao del Sur; 3 Agusan; 4 Davao; 5 Cotabato; 6 Bukidnon; 7 Misamis Orientalis; 8 Lanao del Norte; 9 Misamis Occidentalis; 10 Lanao del Sur; 11 Zamboanga del Sur; 12 Zamboanga del Norte; 13 Negros Orientalis; 14 Negros Occidentalis. The stars mark the approximate origin of two provenances of *E. deglupta* (seed lots S9408 and S9291; see Chapter 9, p 177) which were used in controlled environment studies and also in field trials in Papua New Guinea. Apart from these occurrences in Davao (4) and Cotabato (5), specimens have been collected from Zamboanga (11, 12), Agusan (3), Surigao del Sur (2) and Misamis Orientalis Provinces.

The most extensive stands of *E. deglupta* occur on New Britain. Most of these have been mapped in detail (Figures 2.4, 2.5).

Although Maiden (1910) lists a specimen from Namatanal, New Ireland, recent ground and aerial reconnaissance has failed to locate any natural stands. However, as sites which appear suitable for its growth occur (e.g., Weiten-Kamdaru Valleys), it is possible *E. deglupta* may have been present at the beginning of the century. The specimen cannot be checked as it was in the Berlin Herbarium burnt during World War II.

2.6 FACTORS AFFECTING DISTRIBUTION

Distribution over the natural range is very discontinuous. It is absent from many apparently suitable streams inside the boundary of its present day occurrence.

Natural stands occur where mean monthly maximum temperatures range between 75 and 90°F (24-32°C) in lowland areas and 55 to 80°F (13-27°C) for highland areas (above 300 m altitude). Relative humidities average between 78 and 90 per cent in the lowlands and 60 to 80 per cent in the highlands.

It would seem that rainfall is a dominant factor in the distribution pattern. The naturally occurring stands are within an annual rainfall range of 100-200 inches (2540-5080 mm) per annum with a mean near 120 inches (3050 mm) without any prolonged dry season (Davidson, 1968).

Another important factor in distribution is the carriage of seed by water. The seed is small enough to be carried on the surface or in suspension, depending on its size and weight, and most of the stands in existence today have an obvious riverine

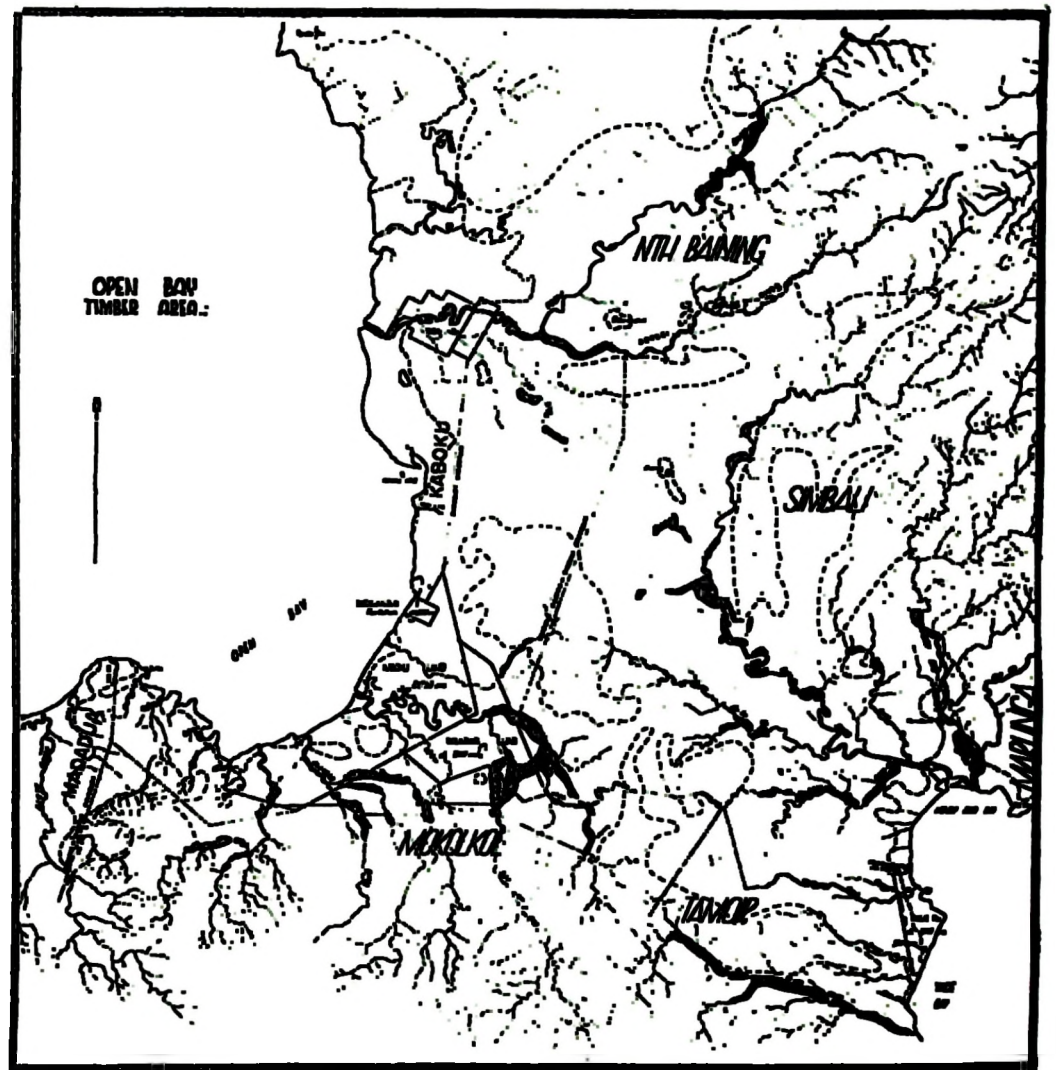


FIGURE 2.4 Riverine stands of *E. deglupta* (black), Open Bay Timber Area, New Britain.



FIGURE 2.5 Map of the Toiru-Pandi Timber Area, New Britain. Extensive riverine stands of *E. deglupta* are shown. Non-riverine stands occur on the slopes of Mt Ulawun, an active volcanic cone.

origin where floods deposit seed and alluvium on sandbanks in bright sunlight.

This type of seed deposition is a balance between seed size (weight) and stream velocity. Young *E. deglupta* stands are frequently found on the convex sides of river curves or at other sites where stream flow is impeded. It is unusual to find dense regeneration more than a few chains from a stream.

A clean seed bed is essential for regeneration. The young seedling, minute at first, is easily damaged. Bright sunlight is required during most of the day for the young seedling to develop quickly. Under conditions of continual flooding and deposition, mortality is high, but this is offset by the abundance of propagules and very rapid early growth. The author has observed as many as 200 young seedlings per square foot (1800/sq m) on a sandbank in the Keravat River.

The ability to colonize unstable soils gives *E. deglupta* an enormous initial advantage over rainforest species. In contrast, it cannot regenerate in shade beneath rainforest.

It is apparent that these factors could cause successive populations of *E. deglupta* to occur further downstream with time. It is conceivable that, on many suitable rivers, *E. deglupta* has been forced out altogether. The most extensive areas are found on New Britain probably because this island is more recent geologically and volcanic activity still provides favourable non-riverine sites inland.

E. deglupta occurs on soils from a wide range of parent materials from acid pumice to varied alluvia. The tree is tolerant of the wet sites associated with creek or river beds where water

is moving but will normally not tolerate stagnant swamp sites and water-logged soils.

Man has further aggravated the discontinuity of distribution. He is primarily responsible for accelerated disappearance of the species in some areas of its range, as *E. deglupta* sites generally represent prime agricultural land. One of the highest altitude stands on the Callawan River, Davao del Norte, Mindanao (and thus an important source for breeding purposes) will probably be eliminated within two years by agricultural activity unless action is taken to preserve it. Lower down the same river, 60 per cent of one of the largest riverine stands in Mindanao has been destroyed by agricultural activity in less than two years.

Fire can be a destructive or beneficial agent. The species has very thin bark and is particularly susceptible to fire. Fire is responsible for the disappearance of *E. deglupta* from the *Octomeles sumatrana* association. However, fire can lead to large tracts of even-aged forest, as for example, that reported by Lane-Poole (1925) where the destruction by fire of an area of mixed *E. deglupta* and rainforest on the Henry Reid River, New Britain, in 1916 was followed by prolific regeneration of *E. deglupta* on the ashbed.

Landslides and volcanic disturbance provide sites for individual tree or small stand regeneration. This regeneration often takes place many miles from the nearest *E. deglupta* stands.

The possibility that the very small seeds (up to 450,000 viable seeds/ounce or 16,000/gram) may be transported by strong wind currents cannot be discounted. The part of birds or insects as vectors of seed distribution has not been established.

2.7 FOREST TYPES AND ASSOCIATIONS

E. deglupta forms extensive pure stands of often more than 50,000 super feet (118 m³) to the acre on New Britain (Plate 2.1). Banks of alluvium along the main streams are colonized after the water level falls (Plate 2.2A). These stands may form a series of age classes rising terrace-like from the stream in coastal rainforest. The regeneration may be dense at first but thins later with competition and subsequent flooding damage. For some time, there is little undergrowth on the rather harsh regeneration sites, but following amelioration of the site by young *E. deglupta*, dense thickets of grass, wild ginger (Zingiberaceae) and low shrubs appear followed by invasion of shade tolerant primary forest species such as *Pometia pinnata* Forst., *Dracontomelum mangiferum* Bl., *Pterocarpus* L., *Homalium* Jacq. and *Celtis* Tourn. species forming a two-layer forest. In Mindanao, *Saccharum* L., *Calophyllum* L., *Casuarina* L. and *Macaranga* Thou. are among the species invading *E. deglupta* sites, often as a result of man's activities.

No significant regeneration of *E. deglupta* occurs after this stage. Mature stands are three-layered with *Gnetum* L., *Horsfieldia* Willd., *Myristica* L., *Calamus* L. and primary forest seedling regeneration as the lowest layer.

The *E. deglupta* dominants become overmature (Plate 2.2B) and disappear leaving typical three-storey rainforest. The mixture of rainforest and *E. deglupta* can be seen at all stages of ecological succession if one proceeds at right angles away from a stream course.

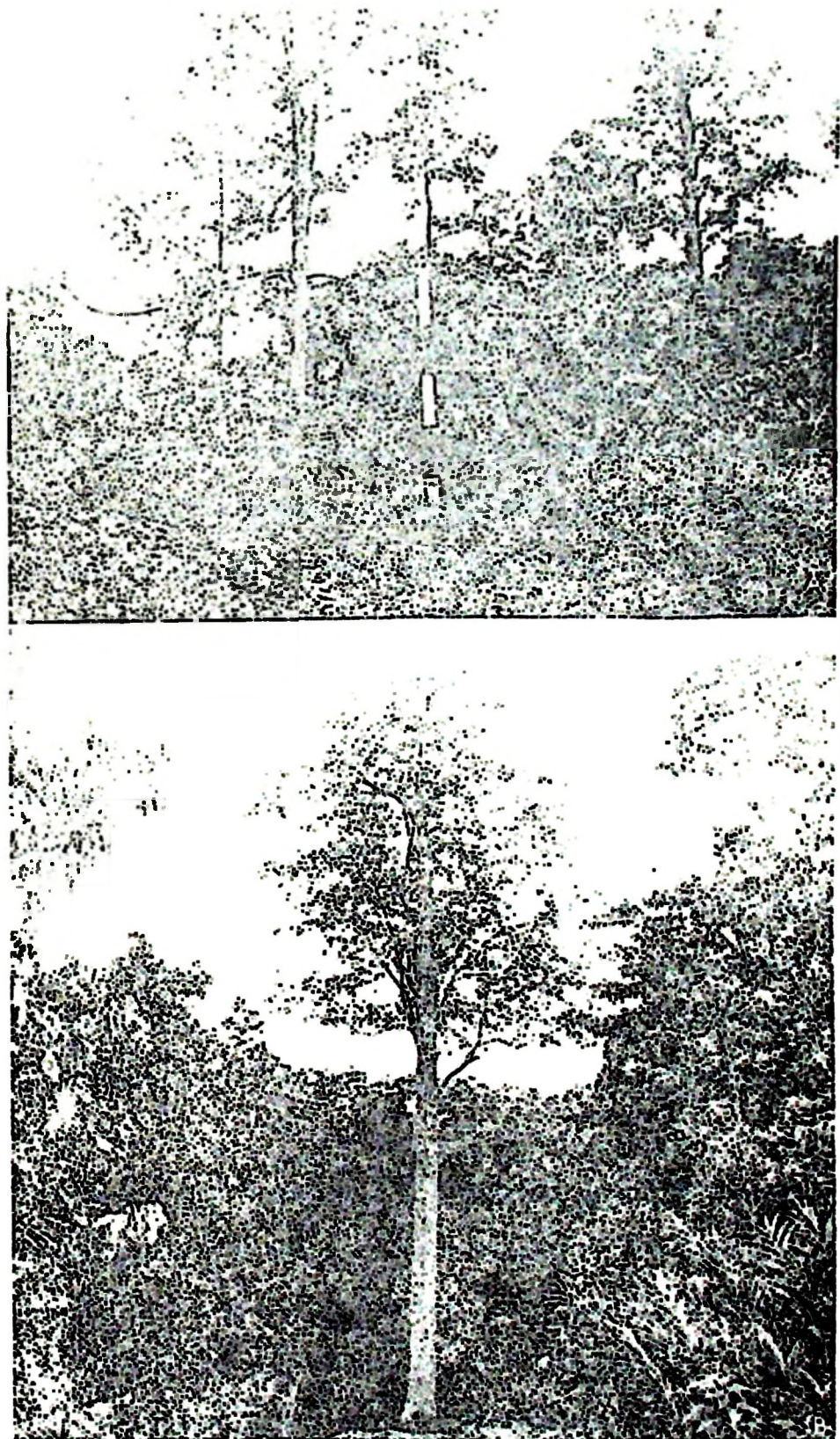


PLATE 2.2 A. Regeneration consisting of several age classes, in gravel on the banks of the Keravat River, New Britain. B. A veteran *E. deglupta* tree near the Keravat River. Height: 220 ft (67.1 m), girth above buttress: 28 ft (8.5 m). The scale is marked in feet. 1 ft = 0.3 m.

The ecological succession described above is typical for the whole of the natural range. Variations do exist and these are caused through modified environmental factors or outside influence. For example, frequent interruption to the succession can be caused by a sudden change in a river's course destroying rainforest and allowing regeneration of *E. deglupta* on a clean seed bed.

Following logging and cultivation by man in areas suitable for *E. deglupta*, it becomes a dominant among secondary forest species such as *Sarcocephalus* Afzel. ex R.Br., *Hernandia* Plum ex L., *Mallotus* Lour., *Macaranga*, *Terminalia* L. and an occasional *Homalium* or *Vitex* Tourn. ex L. left unlogged.

Casuarina species occur as understorey in many stands such as those on the upper slopes of Mount Ulawun (Figure 2.5) and in Mindanao.

A common riverine association with *Ocotomeles sumatrana* occurs on the Henry Reid, Keravat, Warangol and Vudal Rivers of the Gazelle Peninsula, New Britain. Both species regenerate simultaneously and have similar light tolerance and growth rates. This association is more resistant to rainforest invasion but constant burning by man favours the fire-resistant *Ocotomeles* over the very susceptible *E. deglupta*.

The isolated veteran specimens clinging to sides of steep gorges in river headwaters and on pumice ridges of the Gazelle Peninsula, New Britain, are probably the last remnants of the final stage of ecological succession in this species.

In all of the above cases, natural succession from pure *E. deglupta* forest to rainforest is a continuing process interrupted only by stream changes, volcanic activity, landslides, fire or human endeavours. However, around the active volcanoes on New

Britain invasion of rainforest is prevented by the unusual ecological conditions. *E. deglupta* occurs in a static association with palms and *Casuarina* around the tree-line of Mount Ulawun at 4,500 feet (1373 m) altitude (Mount Ulawun is a perfect, active volcanic cone rising from sea level to 7,533 feet (2298 m) in under six miles (9.7 km)). The eucalypt is stunted and barely surviving. The association is kept static by frequent volcanic activity, steep topography, exposure, heavy runoff and shallow soil. Very heavy rainfall of several hundred inches per annum causes sheet erosion on the steep upper slopes and a clean seed bed of rubble and mineral soil is maintained enabling continual regeneration.

The slopes of the mountain are deeply dissected through the lava crust and underlying coarse conglomerate layers. Materials carried by these torrents are continually deposited over large areas of the lower slopes and along the banks of coastal streams. The fast growing *E. deglupta* successfully colonizes these deposits whereas the slower growing rainforest species are destroyed by successive deposits or erosion.

2.8 GROWTH AND YIELD

(a) Natural stands

The mature trees are very large. Lane-Poole (1925) states 'This species comes under the category of giant gums for it towers to a height of 260 feet and yields timber which in size and quality rivals that of the great gums of Australia.'

The present author has measured a veteran tree 228 feet (70 m) and 22 feet (6.6 m) girth above buttress on the Keravat River, New Britain (Plate 2.2B). Other sample trees in New Britain have yielded a log length of 136 feet (41 m) with a solid content of 25,000 super feet hoppus (75 m^3). The main bole was usually straight and cylindrical; however buttressing, often reaching 10-12 feet (3.0-3.6 m) in height was frequent on specimens growing on river alluvia and non-stable soils (Heather, 1955).

The forest resources of New Britain were assessed by the Army during the Second World War (Australian Military Forces, 1945). The area of pure stands was estimated at 25,000 acres (10,000 ha). Much of this included poor stunted growth and young stands. Average plot volume in merchantable stands was 25,000 super feet hoppus/acre ($185 \text{ m}^3/\text{ha}$) the best plot carrying 80,000 super feet hoppus/acre ($590 \text{ m}^3/\text{ha}$). The largest size tree recorded was 25 feet (7.6 m) girth above buttress and 200 feet (61 m) in height. About 100 million super feet hoppus ($300,500 \text{ m}^3$) was estimated to be on the slopes of Mount Ulawun near Uiamona. The remaining 60 million super feet ($180,000 \text{ m}^3$) estimated occurred in varying quantities along some twenty streams.

Excellent stands were found on the Angen, Lula, Awit and Bogus Rivers on the South Coast and along the Pandi and Balima Rivers of the North Coast.

The species has also been found in riverine stands along the Toriu, Mavelo, Powell, Ip and Sai Rivers of the Open Bay Area (Figure 2.4). The Sai River carried half the volume in the area, some stands being located on lower slopes some distance from the river. Standing volume was approximately 29,200 super feet/acre

(170 m³/ha) in pure stands but older trees may have some 20 per cent defect (pipe) not considered in this figure.

In the Ania-Kaplura Area the species is found on the slopes of Mount Bango and along the Biloml, Gavuvu and Kaplura Rivers.

E. deglupta is located along the banks and flood plain of the Pandl, Balima and Toiru Rivers and minor streams in the Toiru-Pandl area and around Mount Ulawun (Figure 2.5). Recent estimates for total volume exceed 50 million super feet (117,600 m³) spread over 12,600 acres (5040 ha) of almost pure stands.

Little information is available from other areas of the distribution. Zleck (1971, personal communication) reported that *E. deglupta* on the mountain slopes near Kebo, West Irian, reached an estimated 160 cms diameter, 50-60 m height and a volume of 35-40 m³ per tree.

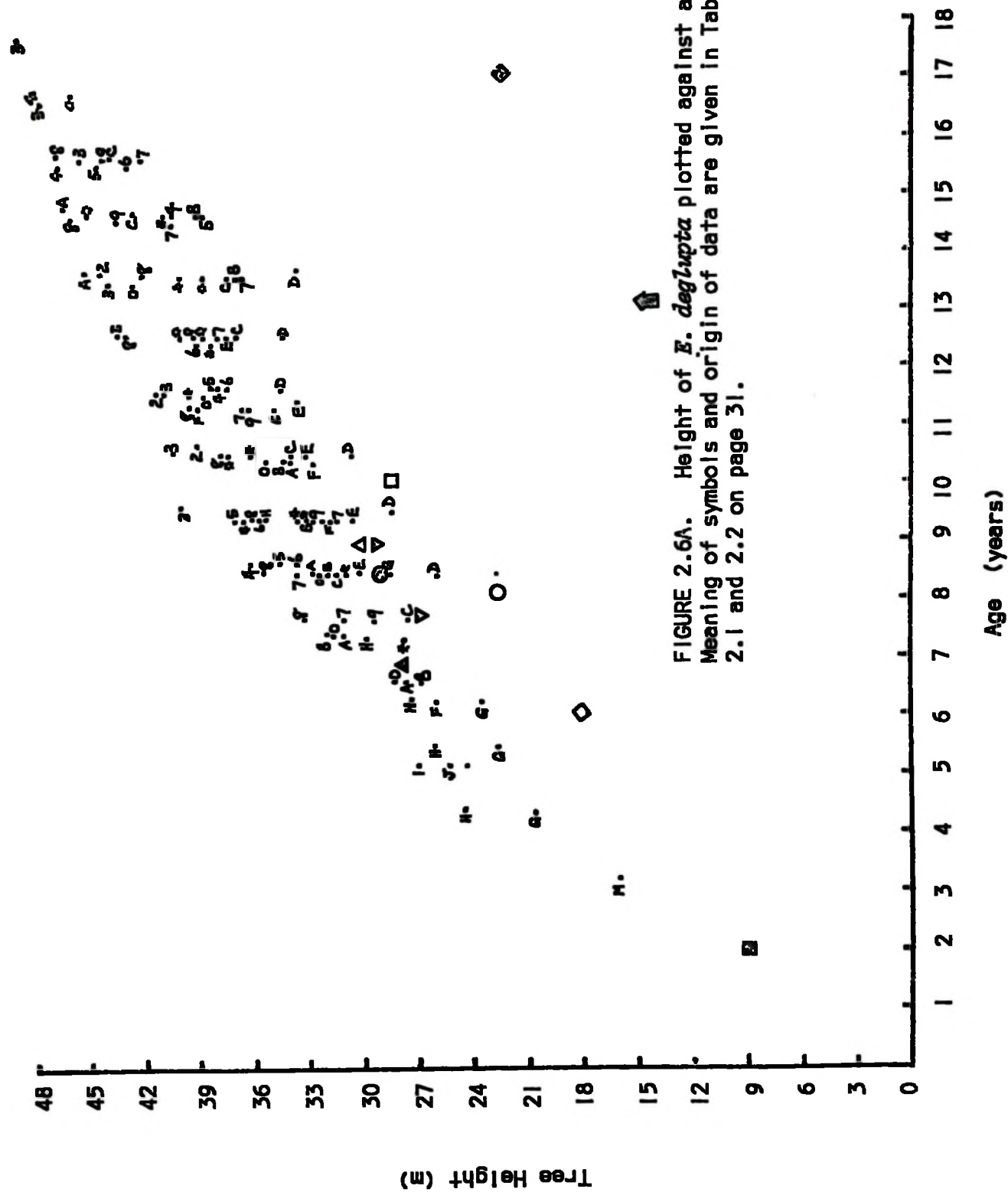
(b) Indigenous plantations

In Papua and New Guinea, over 1,000 acres (405 ha) of experimental plantations have been established (frontispiece). These plantations occupy former *E. deglupta* sites. Initial growth rates are very rapid. Some growth figures are summarized in Figure 2.6. Plot descriptions relating to this Figure are given in Table 2.1.

Extensive plantations are being established on Mindanao but growth information is not yet available.

(c) Growth as an exotic

Eucalyptus deglupta has been planted in trials in many parts of the world. Information concerning these trials is contained



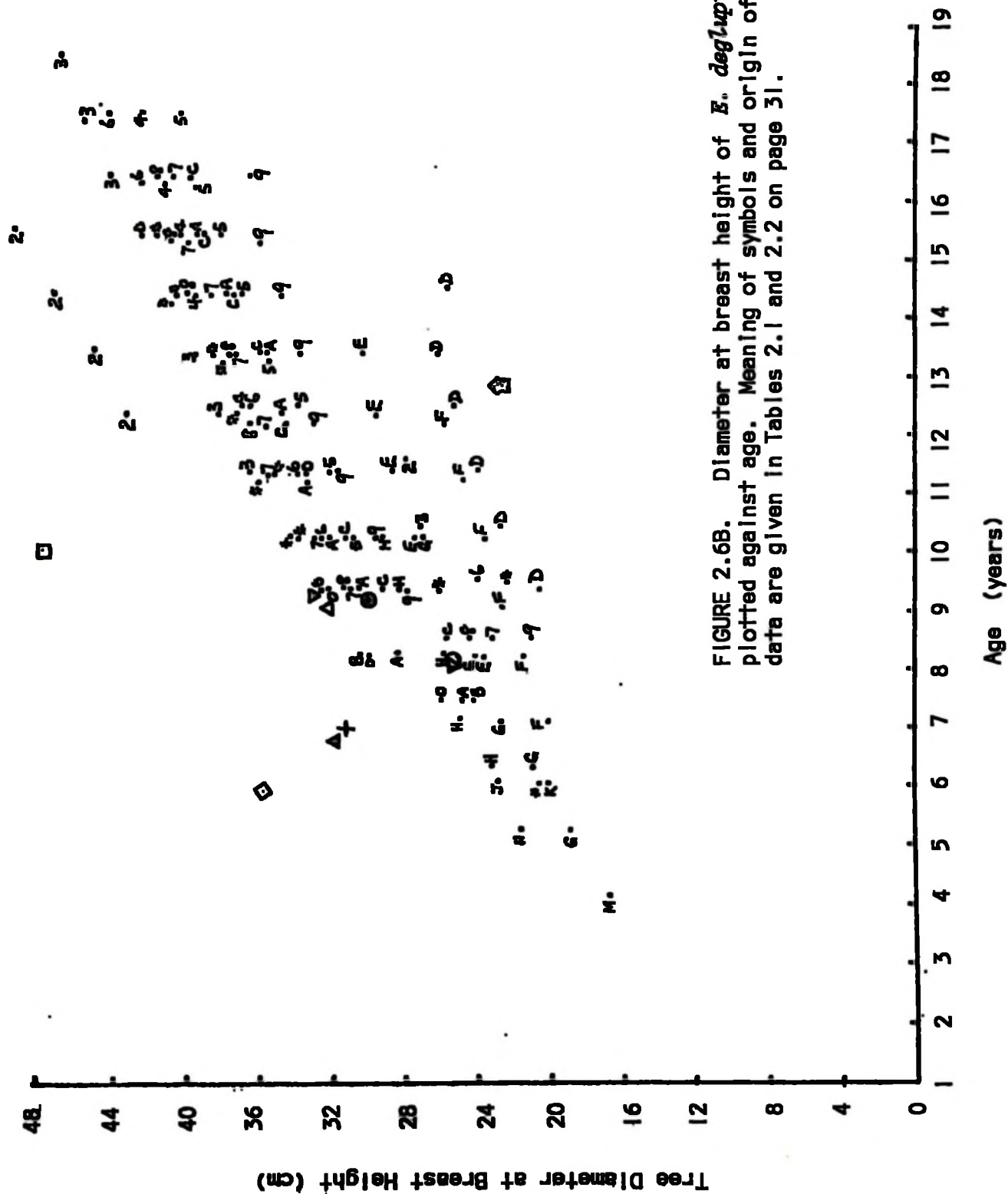


FIGURE 2.6B. Diameter at breast height of *E. deglupta* plotted against age. Meaning of symbols and origin of data are given in Tables 2.1 and 2.2 on page 31.

TABLE 2.1 SYMBOLS USED ON FIGURE 2.6 AND THEIR MEANING

Numbers and letters refer to permanent growth
Inventory plots at Keravat, New Britain.

Symbol on Graph	Growth Plot No.	Compartment and Logging Area	Year of Planting
3	3	4 Fryar	1951/52
4, 5, 6	4, 5, 6	7, 9, 11 Fryar	1952/53
7, 8	7, 8	12, 13 Fryar	1953/54
9	9	Fryar	1953/54
O, A, B, C	10, 11, 12, 13	14 Fryar	1954/55
D, E	14, 15	15 Fryar	1955/56
F	16	2 Kamarere	1957/58
G, H	17, 18	3 Kamarere	1958/59
I, J, K, L	19, 20, 21, 22	4 Little Vudal	1962/63
M	23	5 Little Vudal	1964/65

TABLE 2.2 SYMBOLS USED ON FIGURE 2.6 TO INDICATE GROWTH OF
E. DEGLUPTA AS AN EXOTIC

Symbol	Location of Plot
▲	Mt. Austen, Guadalcanal, 200m.a.s.l.
▼	Rove, Guadalcanal, 3m.a.s.l.
●	Pasir Awi, Java, 150m.a.s.l.
○	Buitenzorg, Java, 250m.a.s.l.
▽	Pasir Hantap, Java, 650m.a.s.l.
△	Šumberwringen, Java, 800m.a.s.l.
■	Cpt. I, Mpanga Res., Uganda
□	Cpt. I, Mpanga Res., Uganda
◇	Nokowa Forest, Uganda
◆	Oda, Gold Coast
+	Belize, British Honduras
⬛	Gadgarra, Queensland, Australia

In Table 2.2. Growth figures have been superimposed on the previous graphs for indigenous plantations (Figure 2.6) and are identified by the symbols given in Table 2.2.

2.9 PRODUCTS AND USES

Eucalyptus deglupta has a red-brown heartwood and a white to pale pink sapwood. Shrinkage and collapse appear to be slight. The wood from natural stands is moderately durable and suitable for interior and protected exterior use. Traditional uses have been heavy construction, furniture, scantling, flooring and boatbuilding. Plantation grown timber has been used recently for similar purposes.

Some preliminary tests have been made on the suitability of the species for pulp production. Von Koeppen (1958) carried out a pulping study on eight butt samples of *E. deglupta* from a five year old Keravat plantation. Trees were between 50 and 90 feet (15 and 28 m) in height and samples two feet (0.6 m) long with centres at three feet height were taken. Von Koeppen found that trees of varying diameter showed little variation in main chemical components. This similarity between trees is an advantage in obtaining chemically uniform pulp. Von Koeppen concluded that *E. deglupta* had a chemical composition similar to temperate zone hardwoods, except for the high ash content. The fact that the plantation grown trees were young appeared to account for the low average fibre length.

The wood was pulped by sulphite and sulphate processes. Pulps prepared from different trees were similar in their yields, overall strength properties, lignin and pentosan contents. Von Koeppen's results showed that the pulps of *E. deglupta* are similar to those

obtained commercially from eucalypts grown in south-eastern Australia but alkali requirements may be greater. The comparison between hand made and machine made chips revealed no marked overall decrease in strength as has been found with *Araucaria hunsteinii* by von Koeppen and Sitzman (1954). This can be attributed to the smaller fibre length and fibre diameter of *E. deglupta*.

Another series of tests has been made on the paper making possibilities of five year old *E. deglupta* grown as an exotic in plantations in the Brazzaville Congo (Petroff, 1965). Petroff concluded that *E. deglupta* pulp was satisfactory in mechanical and chemical aspects.

A more recent small study has been carried out on older trees obtained from Keravat plantations by the Sanyo Pulp Company of Japan (unpublished). These were found suitable for pulping.

Tests have been carried out on sample logs of *E. deglupta* from Keravat, New Britain, to ascertain its suitability for match production by F.M. Forests Pty. Ltd., of Grafton, New South Wales, Australia. It would appear from this small test that *E. deglupta* plantation grown trees are unsuitable for 0.084 inch (2.1 mm) match stick veneer and 0.027 inch (0.69 mm) matchbox veneer. However, results were very variable, one billet 14 inches in diameter, yielding 100 per cent recovery down to a four inch core.

Further tests are recommended as possible degrade during transport could have occurred and the original sample may not have been representative. For very thin veneers difficulty with splitting and curling will be experienced because of the large vessels in this species.

It would appear, from these investigations, that utilization of *E. deglupta* for reconstituted wood products or sawn timber would present few difficulties. Its use in peeling applications has not been sufficiently investigated.

CHAPTER 3

MEASUREMENT OF WOOD PARAMETERS OTHER THAN DENSITY

3.1 INTRODUCTION

The physical and mechanical properties of wood are related to the composition and arrangement of the various types of tissue which comprise it and to the shape, size, wall thickness and structure of the cellular components.

Eucalypt wood has a complicated structure with considerable diversity in types and arrangement of cells. In a single species the arrangement is fairly constant and may be used for taxonomic purposes, but the dimensions, shape and relative proportions of component cells and tissues may vary over a wide range, thus modifying the related physical and mechanical properties. Much of this variation may be random but systematic trends exist in some features and these must first be investigated before the wood can be characterized.

In *Eucalyptus deglupta* wood (Plate 3.1A, B, C, D), the fibres are short (0.6-1.4 mm approximately), minute in cross-section (10-15 μ approximately), and systematically arranged in files only in the radial direction on the transverse surface.

Interspersed among the fibres are small, thin walled parenchyma and large diameter vessels which vary in shape, size and distribution, the whole being interrupted by the rays which usually comprise a significant proportion of the wood volume.

To characterize a wood sample, information is needed on the length and cross-sectional dimensions of the elements and also the

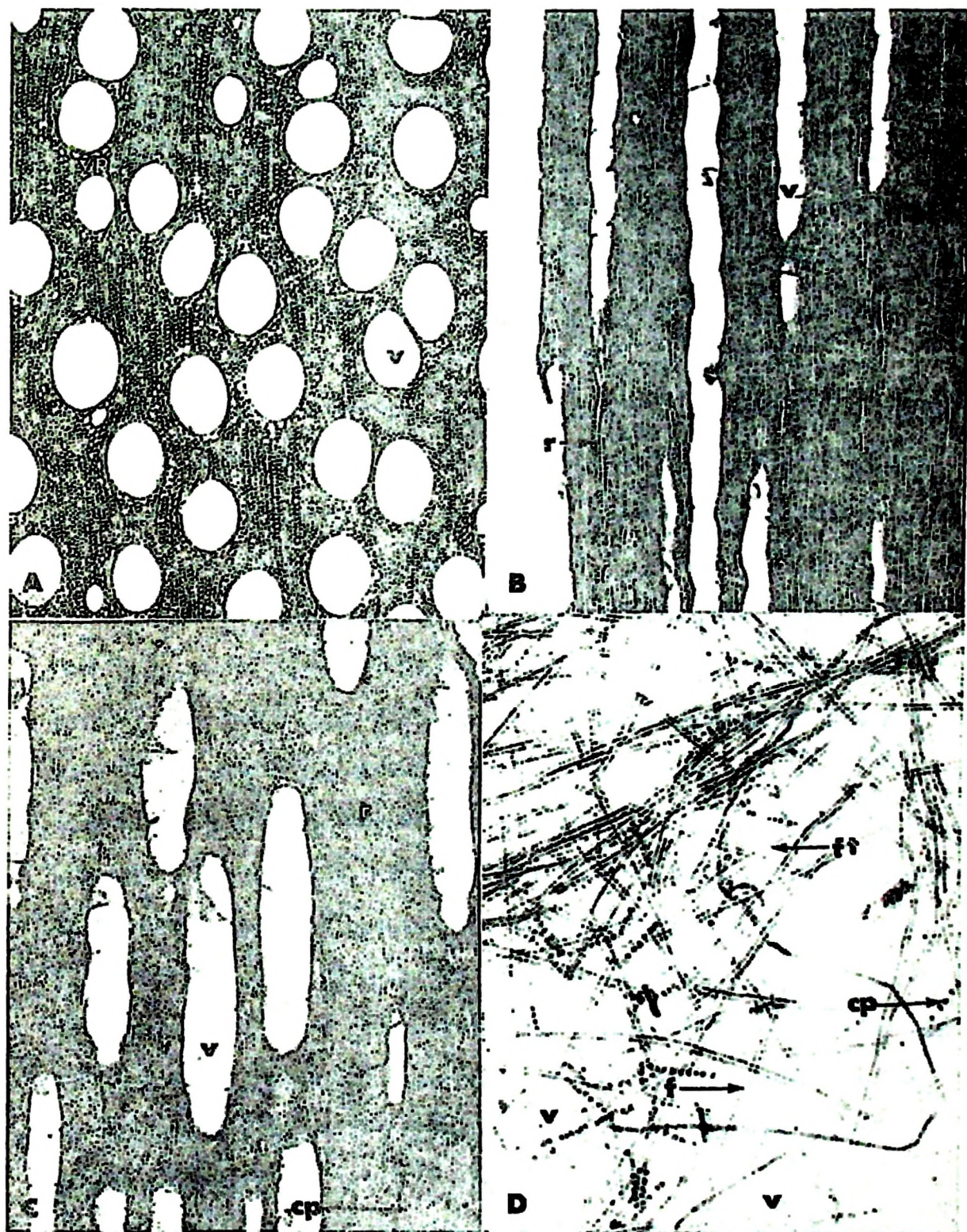


PLATE 3.1 *E. deglupta* wood. A, transverse section; B, tangential longitudinal section; C, radial longitudinal section. All approximately x30. D, macerated wood x 60. v = vessel, f = fibre, r = ray, vp = vertical parenchyma, cp = chambered vertical parenchyma, ft = fibre tracheid.

proportion of the total wood volume occupied by rays, vessels fibres and parenchyma. Because the relative amount of vertical parenchyma was small and essentially paratracheal, this was included along with fibre tissue in proportional tissue estimations. *E. deglupta* wood contains libriform fibres and a small proportion of fibre-tracheids. Only uncut libriform fibres were measured in the fibre length study while fibres and fibre-tracheids were not distinguished for fibre cross-sectional measurements.

The measurement of wood elements occupies considerable time and effort, being repetitive and tedious and, while rapidly fatiguing, must demand a high degree of competence and accuracy of observation to obtain statistically reliable means.

The methods described in this Chapter formulate rules for compiling means from sets of measurements on the one sample, for reconciling conflicting results, and for maintaining a consistent standard of measurement over long periods of time. Whenever microscopic and other repetitive measurements made such demands on a single observer that individual bias and mistakes could develop, an automatic check of results was instigated which almost certainly justified the extra effort. In practice, this required duplication of up to one-fifth of observations but eliminated the necessity for periodic checks by other observers and non-routine comparison and correction of bias which could lead to abnormal results from a single observer.

In each section, short notes are given to justify the selection of a particular parameter for measurement. Various ratios of parameters are also considered.

3.2 FIBRE LENGTH (FL)

Various investigations (see for example Echols, 1955; Jackson and Green, 1957, 1958; Dadswell *et al*, 1961) have indicated that cell length is genetically controlled and it is known to be a factor affecting the properties and utilization of both wood and pulp (Wardrop, 1951; Dadswell *et al*, 1959). Dinwoodie (1961) has published an excellent review on cell length. However, much of this work was carried out on softwoods and insufficient data are available on cell length in hardwoods, especially eucalypts.

Wood maceration involved taking small chips and heating them in a 1:1 (v/v) mixture of glacial acetic acid and 100 vol hydrogen peroxide at 95°C for four hours in a water bath. The digestion mixture was flushed from the delignified chips with water and final fibre separation performed by shaking vigorously in water. Slides were prepared using the method of Echols (1961). The fibre suspension was poured over glass microscope slides submerged in water. After fibres had settled randomly over the slide the water was drained off. Temporary mounts were prepared by adding a small drop of glycerine before the coverslip was placed in position.

Fibre images were projected at 60-100 magnifications using a Gillett and Sibert Conference Microscope (Plate 3.2A) and whole, undamaged fibres were measured in groups with a mapping wheel according to the rules developed and set out below.

The variability of fibre length within a number of preliminary samples was used

1. to determine the number of observations required to present means with acceptable limits of error and

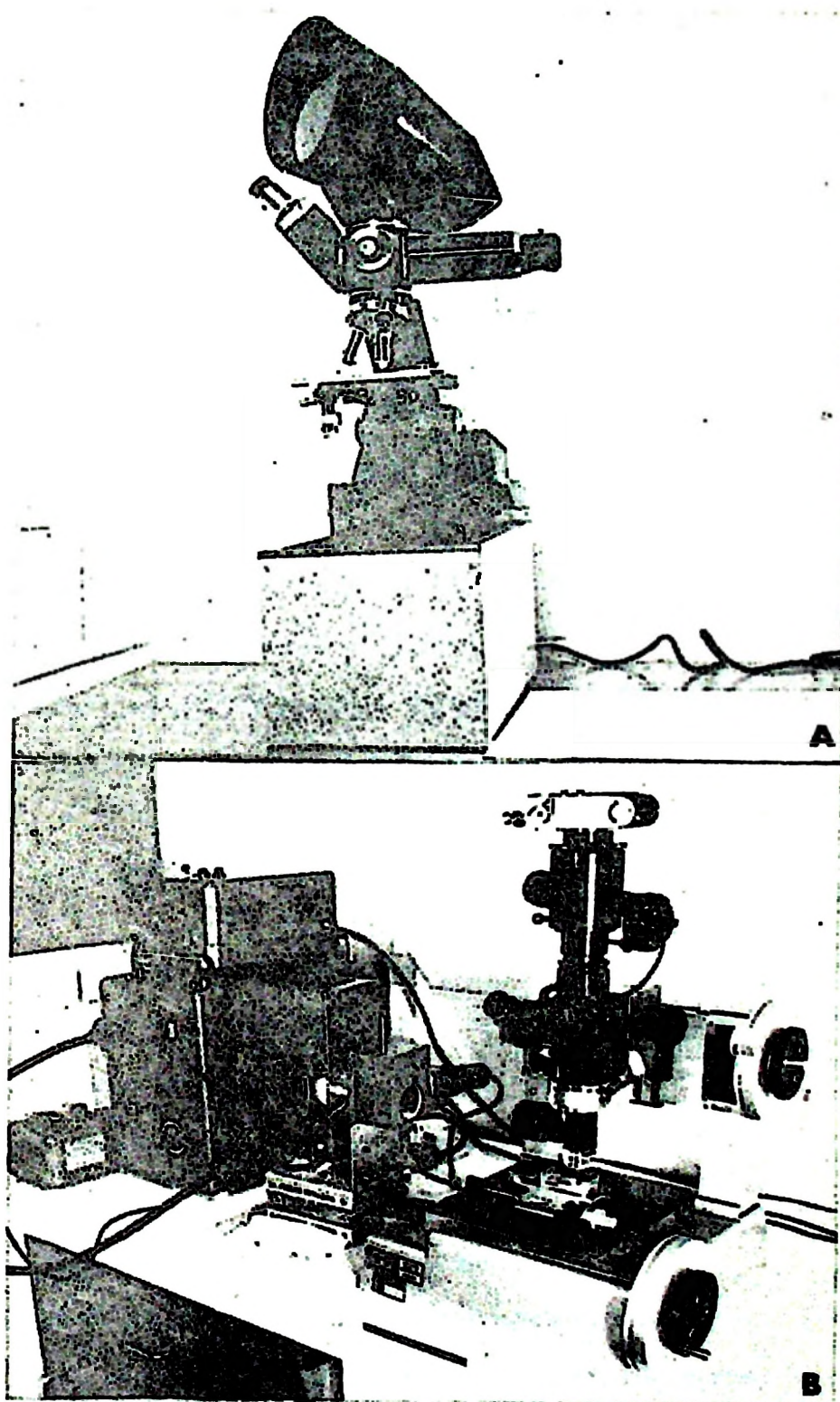


PLATE 3.2 A. Gillet and Sibert Microscope.
B. Dual Linear Microscope

11. to compare results of several observations on one sample.

Four preliminary samples were selected to represent the material to be studied. For short fibres, two specimens were selected near the pith and, for long fibres, two near the bark. To take account of any height effect the two specimens for each were taken at breast height and 30 per cent of final height respectively. Two hundred individual fibre lengths were measured on each of the four samples to determine likely within sample variability.

When these results were plotted as a frequency distribution, the distribution was nearly normal (Figure 3.1). Thus normal distribution statistics may be used to determine sample size. Sample size was determined from a formula of the form

$$n = \left(\frac{\sigma t}{e} \right)^2 \quad (3.1)$$

where n = number of individual measurements required

σ = coefficient of variation of measurements on similar experimental material

t = normal deviate for large samples or Student's t for small samples

e = error percent of the mean required.

A derivation of this formula has been reconstructed in Appendix 1. Some distinction should be made between the normal distribution and Student's t distribution, as these only closely approximate each other if the sample contains about 100 or more individual measurements.

The coefficient of variation for *E. deglupta* fibres varied only slightly with sample origin although the magnitude of the

mean and dispersion about the mean varied considerably (Figure 3.1 and Table 3.1).

A great deal more work is involved in reducing the error from ± 5 per cent to ± 3 per cent because of the extreme exponential nature of expression 3.1 (Figure 3.2).

Consideration of the above discussion and the need for standardisation of laboratory procedures led to 100 fibres being accepted as the unit sample, resulting in less than three per cent error at the 95 per cent confidence level.

If separate groups of measurements are carried out on different parts of the same sample population, the variability within the population will, of itself, result in differences between the means obtained for those parts. This variability can be used as a basis for accepting or rejecting a particular result.

Two slides were made and two groups of twenty-five fibres were measured on each thus arriving at a total of 100. If four groups of observations each one quarter of the total ($n/4$) are made, the expected percentage difference (d) between the mean values can be shown to be not more than

$$d = \frac{2 \sigma t}{\sqrt{n}} \% \quad (3.2)$$

for 95 per cent of cases (when $t = 1.96$), using similar notation to that above (Appendix 1). Any mean differing from the others by more than this percentage is rejected. Further measurements are taken until one which satisfies the accuracy requirements is obtained. This is then pooled with any previously accepted scores until a total of four is obtained. If further measurement failed to narrow the prescribed allowable difference between sub-sample means. It was possible a one in twenty chance had occurred (allowed for

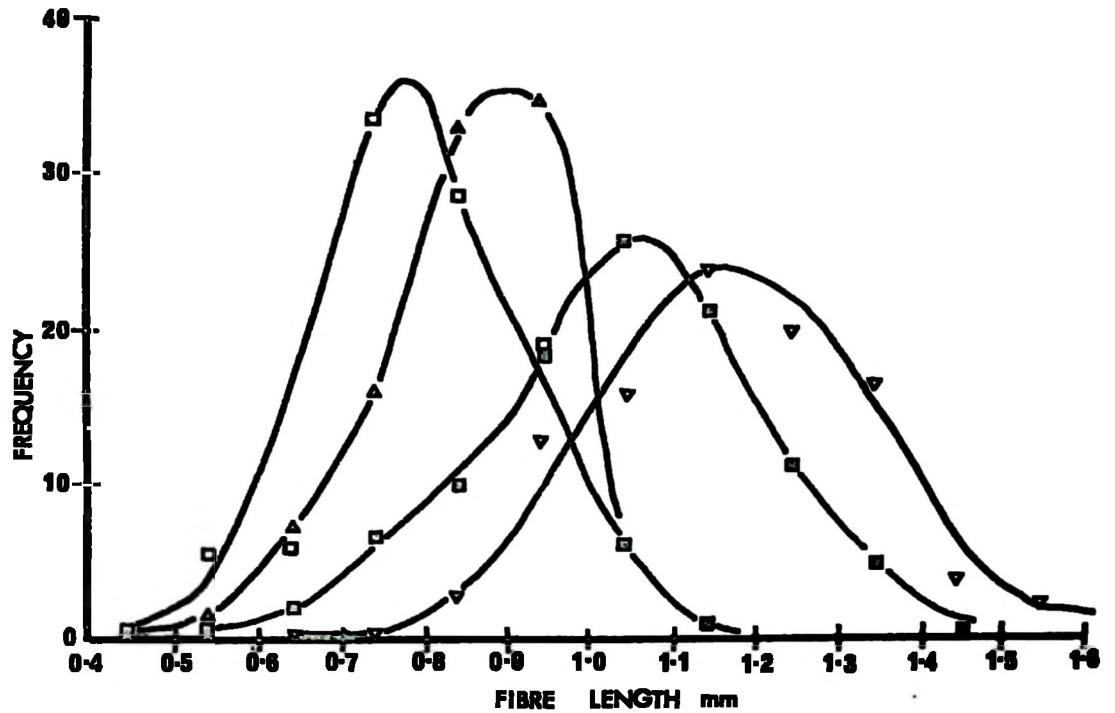


Figure 3.1 Fibre length distribution curves. Open squares: breast height, 2.5 cms from pith, solid triangles: breast height, 12.5 cms from pith, solid squares: 30 per cent height, 2.5 cms from pith, open triangles: 30 per cent height, 12.5 cms from pith.

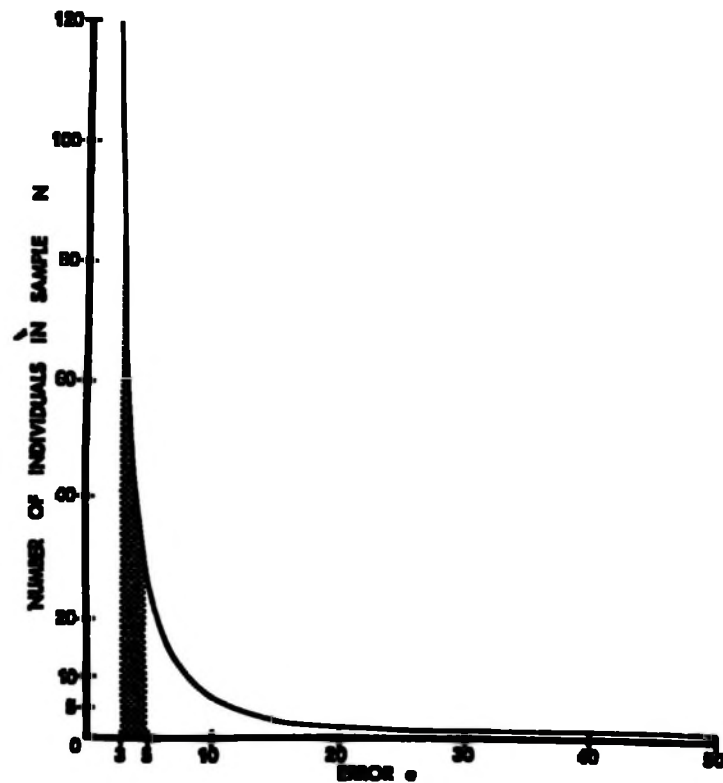


Figure 3.2 Graph of $N = \left(\frac{\sigma t}{e}\right)^2$, when t and σ are held constant.

TABLE 3.1 FIBRE LENGTH SAMPLE DETAILS*

Sample Origin	Mean $\bar{x}$	Variance σ^2	Standard deviation σ	Standard error S.E.	Coefficient of variation C%	Number of fibres for 5 per cent accuracy	Number of fibres for 3 per cent accuracy	Accuracy per cent for 100 fibres measured	Confidence limits on 100 fibres (mm)
1. Breast height near pith	0.831	0.0148	0.1216	0.0085	14.63	32	90	2.86	± 0.024
2. Breast height near bark	1.039	0.0266	0.1630	0.0115	15.69	38	106	3.08	± 0.032
3. 30% height near pith	0.859	0.0125	0.1118	0.0079	13.01	26	73	2.55	± 0.022
4. 30% height near bark	1.175	0.0261	0.1615	0.0114	13.74	29	81	2.69	± 0.032

*The normal deviate $t = 1.96$ for 95 per cent confidence level

when choosing $t = 1.96$), assuming errors in actual measurement were the most frequent source of differences between sets of measurements. This became evident when several further measurements did not contribute to a reduction in sub-population variability.

In summary:

- I. Two slides were made for each sample.
- II. Two sub-sets of 25 fibres each were measured on each slide, totalling 100. Individual fibres were not measured. The sub-sets of 25 were summed using a mapping wheel.
- III. Means for each sub-population of 25 fibres were required to agree with each other within prescribed limits or be rejected in favour of further measurements unless it was apparent a 1 in 20 chance had occurred.

These tactics could not ensure perfect results as compensating errors would give the appearance of validity and be impossible to check. However, gross errors such as mis-counting of the number of fibres measured were always revealed.

3.3 FIBRE WALL THICKNESS (W) AND LUMEN DIAMETER (L)

The thickness of the fibre wall of angiosperm wood contributes to its strength, machining ability and pulp quality.

The relationships of fibre diameter and lumen diameter with wall thickness have important bearing on fibre flexibility which in turn affects a number of paper properties (Dinwoodie, 1965).

The cross-sectional and tangential surfaces of small wood blocks, approximately a cube with one centimeter sides were smoothed in a sliding microtome. Specimens were just submerged in water in small plastic troughs and held in place with modelling clay. After

immersion a vacuum of 30 inches of mercury was drawn, held for five minutes, then released, in order to remove air from the specimen so that cell walls would not appear distorted due to differences in the refractive indices of air and water.

Sample size for reliable estimates of mean cell wall thickness and lumen diameter within the blocks was decided using similar reasoning to that for fibre length (Figure 3.3). The distribution for double wall thickness closely approximates normality while that for lumen diameter is slightly skewed to the right. This skewness was insufficient to affect analysis and would probably be less for a larger sample of individual measurements.

The limit of resolution for a visual light microscope is considered to be about 0.2μ under optimum conditions (Smith, 1965), so a precision of $\pm 0.5 \mu$ on individual measurements was deemed adequate. This level of accuracy corresponds to about 12 per cent of the mean for double wall thickness and 6 per cent of the mean for lumen diameter.

A single transverse cut on the wood block intersected the fibres randomly with respect to their length, and measurements of contiguous fibres in the radial direction gave statistically reliable means provided only that the ultimate tips were excluded. Fibres were measured in radial files selected at random. This procedure was preferable to complete random sampling as the coefficient of variation was reduced, fewer measurements were required to obtain a mean of given standard error and measurement time was reduced.

The instrument used in this investigation was a dual linear traverse measuring micrometer fitted with a Leitz Ultrapack Microscope (Plate 3.2B). A 55x water immersion objective, a 1.25 x intermediate stage and a 10x stereoscopic ocular with cross hairs were used giving an overall magnification of 687.5x,

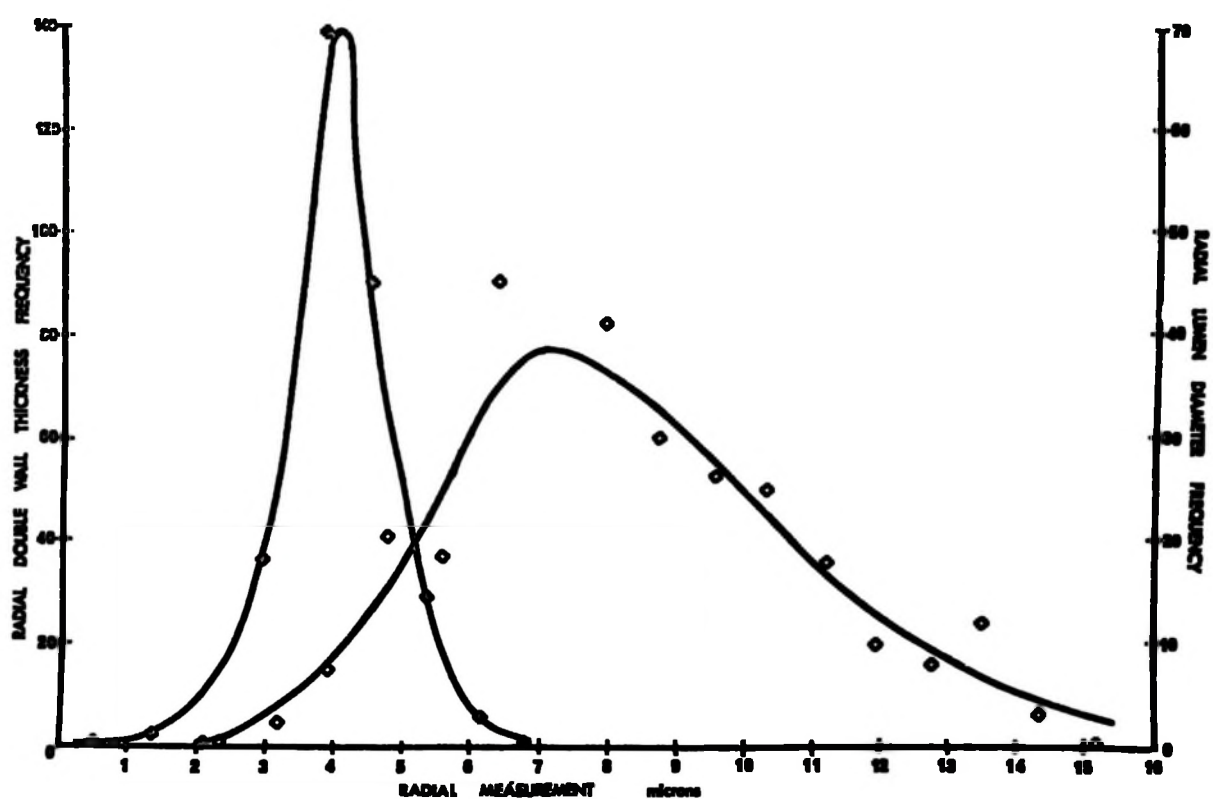


Figure 3.3 Distribution curves for double wall thickness (black diamonds) and lumen diameter (open diamonds).

illumination being provided by a high intensity Xenon arc lamp. The advantages of this instrument and method over others are summarized by Smith (1965). The stain used was an aqueous solution of malachite green and methylene blue.

The structure of *E. deglupta* fibre tissue does not allow easy measurement of fibre walls (Plate 3.3). While the fibres are commonly aligned in radial rows, there is poor alignment in the tangential direction. It was possible to measure wall thickness of fibres in the radial direction because the line of traverse could be orientated through the mid-point of successive tangential walls at right angles in any selected radial row. The lack of orientation of fibres into files in the tangential direction did not allow a succession of cells to be measured without continuous re-orientation of the specimen. Structural features by-passed during measurement included vessels, the diffuse and vasicentric parenchyma and the obvious tips of fibres which often appeared due to adjustment of adjoining fibres during surface growth. The rays are narrow and do not appear to have caused any abnormal dimensional changes to the adjacent fibres.

To facilitate this re-orientation and by-passing radial files of cells, a small mechanical stage with adjustment along two axes at right-angles, was superimposed upon the micrometer traversing table. Thus, adjustments made on the small stage would not effect the micrometer scale drums which were read to the nearest micron. The microscope unit travels to the right and the stage to the left, along the micrometer screws, with the image travelling from left to right in the viewing field. The specimen was orientated accordingly and measurements were made with one bar of the cross-hairs of the ocular orientated horizontally (i.e., radially along the specimen).

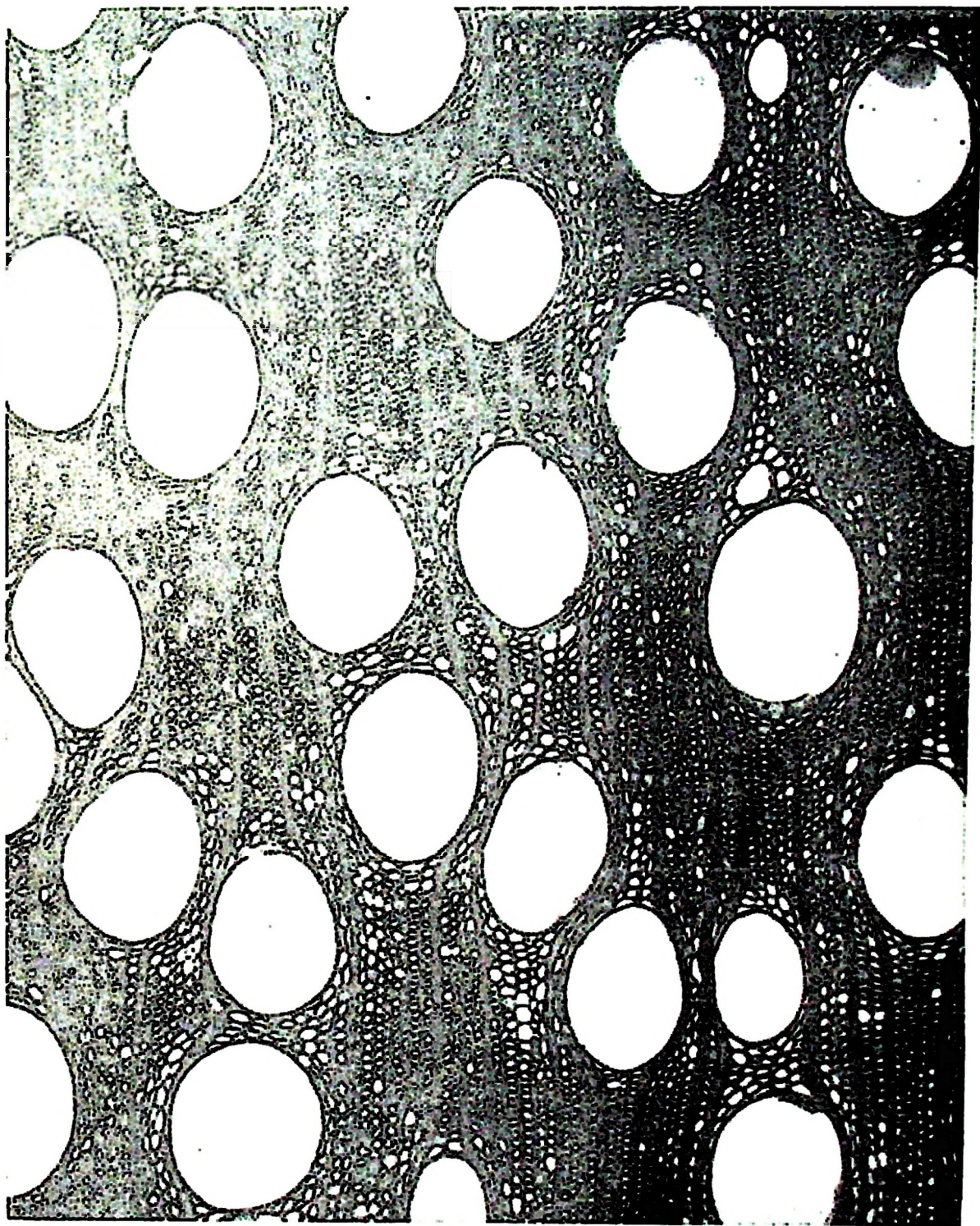


PLATE 3.3 Transverse section of *E. deglupta* wood. Fibres are commonly aligned in radial files while there is poor alignment in the tangential direction. Approximately 150x.

If by passing or offsetting had to be done to find a new radial file of fibres free from obstruction, the mechanical stage was moved forward or back to bring a new succession into view, to left or right to bring the first cell to the cross hair or rotated to make radial alignment more precise.

The advantage of the dual linear scales on the instrument was that combined radial widths of the double cell walls between lumens could be accumulated on one scale and the combined radial width of lumens on the second.

By keeping count of the total number of fibres traversed by means of a hand tally counter, the following parameters could be calculated from each set of radial measurements.

Average fibre double wall thickness ($2W$)

$$2W = \frac{\sum_{i=1}^{\sigma} w_i}{\sigma} \quad (3.3)$$

Average fibre wall thickness (W)

$$W = \frac{\sum_{i=1}^{\sigma} w_i}{2\sigma} \quad (3.4)$$

Average fibre lumen diameter (L)

$$L = \frac{\sum_{i=1}^{\sigma} l_i}{\sigma} \quad (3.5)$$

Average fibre diameter (D)

$$D = \frac{\sum_{i=1}^{\sigma} (w_i + l_i)}{\sigma} \quad (3.6)$$

where

$\sum_{i=1}^{\sigma} w_i$ = width of the accumulated double wall thickness

$\sum_{i=1}^{\sigma} l_i$ = width of accumulated lumens

σ = cell count

The cross-sectional dimensions of an average fibre, representative of the entire specimen block could be determined.

3.4 ARITHMETIC RATIOS OF FIBRE LENGTH, WALL THICKNESS AND LUMEN DIAMETER

A number of ratios of parameters have been derived by various workers in attempts to relate measured variables to properties of the wood or reconstituted wood materials. The importance of parameter ratios has been discussed by Péterl (1952), Runkel (1952), Istas *et al* (1954), Seabra and Ferreirinha (1960) and Chiaverina (1963).

(a) Fibre Length:Diameter Ratio (FL/D)

The fibre length:diameter ratio (FL/D), sometimes called the felting coefficient has been mentioned in the pulp and paper literature, for many years, as one of the fibre parameters associated with paper strength. However evidence to support this has often been put forward in a vague and contradictory manner.

Hägglund (1951) found little evidence from an examination of various softwood species that the FL/D ratio had any appreciable effect on the paper properties.

Péterl (1953) made a large number of observations on tropical hardwood species and concluded that "If a graph is made of the tearing strength as a function of the relative length of the fibre; as compared with the width It can be noted that the points are disposed about a line with a dispersion of about 20%".

Casey (1960) discussing the importance of different fibre properties, stated that "fibre coarseness, or relationship of fibre width to length, is at least as important as fibre length".

Petroff and Normand (1961) also working with tropical woods, were able to establish a good relationship between tearing strength and the FL/D ratio.

Tamolang and Wangaard (1961) found no relationship between FL/D ratio and burst factor, tear factor or breaking strength. Later Wangaard (1962) using three additional species and a modified statistical procedure found some correlation between FL/D ratio and burst and tear factors.

Watson and Dadswell (1964) concluded that the FL/D ratio cannot be expected to provide basic information on strength properties associated with fibre bonding and for tearing resistance, any correlation that can be established with FL/D ratio "is clearly due to a combination of circumstances".

The influence of some FL/D ratios on paper strength properties using data taken from Watson and Dadswell (1964) are given in Table 3.2. The three species have similar FL/D ratios but very different paper strength properties.

Apart from paper strength properties, the FL/D ratio might be important in other properties, such as ease of sheet formation, sheet smoothness and opacity, especially where short and long fibre pulps are blended.

TABLE 3.2 INFLUENCE OF SOME ARITHMETIC RATIOS ON SOME EUCALYPT PAPER STRENGTH PROPERTIES (SULPHATE PULPS)*

	FL mm	D μ	W μ	L μ	FL/D	L/D	1/D	2W/D	2W/L	Breaking length mm	Burst Factor	Tear Factor
<i>E. regnans</i> F. Muell.	0.70	19	3.1	12.8	40	0.67	53	0.33	0.48	10.7	71	81
<i>E. deglupta</i>	0.90	20	2.7	14.6	44	0.73	50	0.27	0.37	8.7	57	104
<i>E. moluccana</i> Roxb.†	0.90	20	6.6	6.8	47	0.34	50	0.66	1.94	3.1	12	32

FL = Fibre length W = Fibre wall thickness 2W = Double wall thickness
D = Fibre diameter L = Fibre lumen diameter 1/D = Reciprocal of fibre diameter

*Source: Watson and Dadsweil (1964)

†Formerly *E. hamphloia* F. Muell. ex Benth. (Johnston and Marryatt, 1965)

(b) Runkel's Ratio (2W/L)

Definite information is available on the influence of cell wall thickness on pulp properties. Runkel (1952) pointed out that thin walled fibres in which

$$2W/L < 1$$

where 2W = double wall thickness

L = lumen diameter

are best because they collapse, become ribbon-like, and provide a large area for inter-fibre bonding. Thick-walled fibres are stiff, resistant to beating, and retain their rounded shape during sheet formation with little area available for interfibre bonding.

E. deglupta and *E. moluccana* fibres have similar length but vastly different 2W/L ratios, the high ratio of *E. moluccana* being accompanied by lower paper strength properties (Table 3.2).

(c) Wall Thickness:Fibre Diameter Ratio (2W/D)

This ratio can be regarded as an expression of fibre density. The ratio will determine the degree of flexibility and collapse of the fibre, both of which control the degree of conformability within the paper sheet and thus the number of interfibre bonds. When expressed as a percentage this ratio is sometimes known as the Isenberg coefficient.

On purely theoretical grounds, 2W/D (i.e., the relative proportion of solids in the cell cross section) should show a high correlation with wood density. Dadswell and Watson (1962) consider that the ratio, cell wall thickness to cell diameter, has a lesser

Influence on pulp strength than wall thickness alone. However, contrary to their view, Dinwoodie (1966) stated that, in the appraisal of factors affecting paper-strength, it was doubtful if one could justifiably discriminate between the parameters $2W/D$ and W . In Table 3.2, parameters $2W/D$ and W bear similar relationships within species.

(d) Lumen Diameter:Fibre Diameter Ratio (L/D)

Positive relationships have been established between tensile (breaking length) and burst strengths and the L/D ratio, sometimes called the coefficient of fibre flexibility (Pétérí, 1952; Petroff and Normand, 1961).

This ratio describes the relative proportion of void to solid in the fibre cross-section so might be expected to show some correlation with wood density. Mottet (1963) noted that in mature forest trees of *Terminalia superba*, the density of the wood increased regularly with age and increase in density was accompanied by a corresponding reduction in the fibre flexibility coefficient.

Dadswell and Watson (1962) consider that this ratio (like $2W/D$ above) is not as important as cell wall thickness in determining pulp strength.

(e) Reciprocal of Fibre Diameter ($1/D$)

This value is numerically equal to the number of fibres per unit length of traverse in the radial direction. It is thus an index of fibre packing density and an indication of the amount of solid material present, thus it would be expected to have some connection with density.

$$1/D = \frac{a}{\sum_{i=1}^a (w_i + l_i)} \quad (3.7)$$

where

$\sum_{i=1}^a (w_i + l_i)$ = total sum of double walls and lumens in micrometer traverse

a = cell count in traverse

3.4 CROSS-SECTIONAL AREA OF FIBRES, FIBRE WALL MATERIAL AND LUMENS

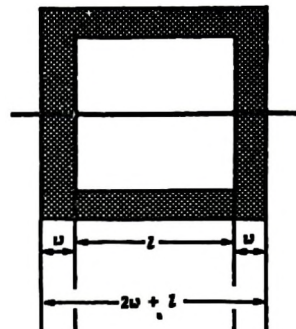
Parameters recording actual amount of fibre wall substance in cross-section are more likely to indicate wood and pulp properties than pure arithmetic ratios of radial measurements as described in the previous section.

If only radial measurements of fibre lumen diameter and wall thickness are obtained or indeed possible to measure with relative ease because of cellular arrangement, the relative cross-sectional areas occupied by wall substance and void will vary with the shape of the cross-section.

If one studies fibre tissue in transverse section (Plate 3.3) most of the fibre cross-sections can be seen to have nearly equidimensional sides.

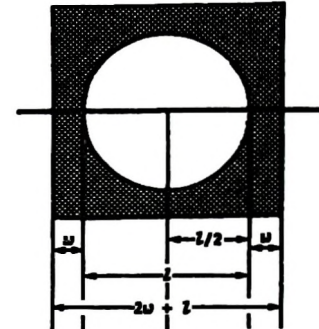
In order to study how this shape would affect the cross-sectional area, five feasible models of fibre cross-sections were devised (Figure 3.4) and cross-sectional area of fibre, wall substance and lumen were obtained in terms of double wall thickness ($2w$) and lumen diameter (l) (Table 3.3).

MODEL 1: SQUARE FIBRE AND SQUARE LUMEN



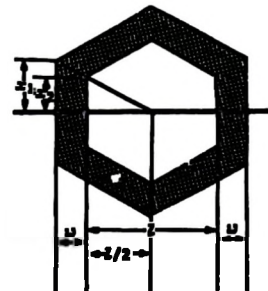
$$\begin{aligned}\text{Fibre area} &= (2u + l)^2 \\ \text{Lumen area} &= l^2\end{aligned}$$

MODEL 2: SQUARE FIBRE, CIRCULAR LUMEN



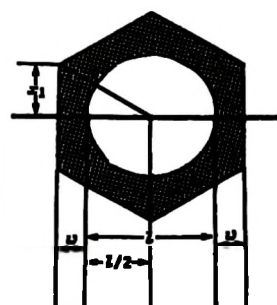
$$\begin{aligned}\text{Fibre area} &= (2u + l)^2 \\ \text{Lumen area} &= \pi r^2 \\ \text{where } r &= l/2\end{aligned}$$

MODEL 3: HEXAGONAL FIBRE AND HEXAGONAL LUMEN



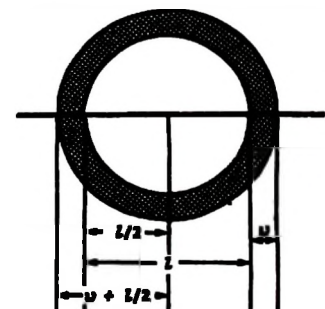
$$\begin{aligned}x_1 &= (u + l/2) \tan 30^\circ \\ x_2 &= (l/2) \tan 30^\circ \\ \text{Fibre area} &= \sum_{i=1}^6 [x_1 (u + l/2)]_i \\ \text{Lumen area} &= \sum_{i=1}^6 [x_2 (l/2)]_i\end{aligned}$$

MODEL 4: HEXAGONAL FIBRE, CIRCULAR LUMEN



$$\begin{aligned}x &= (u + l/2) \tan 30^\circ \\ \text{Fibre area} &= \sum_{i=1}^6 [x (u + l/2)]_i \\ \text{Lumen area} &= \pi r^2 \\ \text{where } r &= (l/2)\end{aligned}$$

MODEL 5: CIRCULAR FIBRE AND CIRCULAR LUMEN



$$\begin{aligned}\text{Fibre area} &= \pi R_1^2 \\ \text{where } R_1 &= (l/2 + u) \\ \text{Lumen area} &= \pi R_2^2 \\ \text{where } R_2 &= (l/2)\end{aligned}$$

Figure 3.4 Models of fibre cross-sections

TABLE 3.3 FIBRE AREAS, LUMEN AREAS AND WALL AREAS (BY SUBTRACTION) FOR FIBRE CROSS-SECTION MODELS IN TERMS OF WALL THICKNESS (w) AND LUMEN DIAMETER* (L)

Model	Fibre Area	Lumen Area	Wall Area
1	$1.000 (2w + L)^2$	$1.000 L^2$	$4.000 (w^2 + wL)$
2	$1.000 (2w + L)^2$	$0.785 L^2$	$4.000 (w^2 + wL) + 0.21 L^2$
3	$0.870 (2w + L)^2$	$0.870 L^2$	$3.480 (w^2 + wL)$
4	$0.870 (2w + L)^2$	$0.785 L^2$	$3.480 (w^2 + wL) + 0.08 L^2$
5	$0.785 (2w + L)^2$	$0.785 L^2$	$3.142 (w^2 + wL)$

*To avoid confusion fibre "diameter" is used as a synonym of fibre "width" for those models not involving circular sections.

When the formulae are inspected, common terms can be found among the models. Fibre area is in terms of $(2u + l)^2$ (i.e., [fibre diameter]²) lumen area in $(l)^2$ and wall area in $(u^2 + ul)$. Thus, it is the magnitude of the multiplying constant which is of importance. For any shape in a series from Model 1 with four sides through Models 3 and 4 with six sides to Model 5 with infinite sides only the constant multiplier for fibre area will vary between 1.000 and 0.785 or about 20 per cent. For the small quantities involved, this is a low order of magnitude.

Model 3 was subjectively chosen as the model to use as this has intermediate coefficient values for fibre area, lumen area and wall area and seemed to represent the most common fibre-cross-section shape present in *E. deglupta* wood (Plate 3.3). The difference between multipliers for Models 4 and 5 with Model 3 is less than ten per cent.

3.5 ARITHMETIC RATIOS OF FIBRE CROSS-SECTIONAL PARAMETERS

(a) Ratio Transverse Area of Wall:Transverse Area of Fibre (WA/FA)

Providing there are no intra-cellular spaces this ratio represents the proportion of wall material in the space occupied by fibres. This ratio when expressed as a percentage is sometimes known as the Multstep coefficient (Ferreira, 1965).

Some relationship of this ratio with density could be expected.

(b) Transverse Area of the Lumen:Transverse Area of Fibre (LA/FA)

This ratio represents the proportion of voids in the fibre tissue, providing the fibres have no space between them. Again some connection with density could be expected.

(c) Transverse Area of the Lumen:Transverse Area of the Wall (LA/WA)

This ratio determines the extent to which the fibre will flex and collapse and should also bear some relation to density.

(d) Reciprocal of Fibre Area (1/FA)

The magnitude of the radial dimensions and the shape of the fibre in cross-section determines the number of fibres in a given area of wood cross-section. The number of fibres per unit area is the reciprocal of average fibre area.

3.6 PERCENTAGE OF TISSUE TYPES BY VOLUME

It is important to discover the relative importance of each tissue type in respect to wood properties as large differences in size and weight occur between differing cell types. The large numbers of small fibres with relatively thick walls would be expected to determine largely the weight per unit volume. The vessels are numerous and large in *E. deglupta* but are thin-walled, so their effect on density is mainly to increase volume without adding weight. To resolve these problems, percentage by volume of rays, vessels and fibres and parenchyma were determined. Fibres

and parenchyma were considered together as the amount of parenchyma present was small, being of diffuse and vasicentric types (Figure 3.1A).

(a) Percentage Rays by Volume

The percentage of the total wood volume occupied by rays can best be determined on the tangential surface of the specimen because rays, once formed, run continuously and radially towards the bark. The percentage area occupied on the tangential surface is equivalent to percentage volume of ray tissue as the rays usually maintain a constant height and shape and these are achieved soon after initiation.

Since some new rays may arise at depth in the block, even in the smallest specimens, measurements were made on both tangential surfaces.

The dual-linear traversing micrometer was again used, the two dials summing ray and non-ray tissue respectively.

A number of traverses were made on both surfaces of several trial blocks. The coefficient of variation between passes over the entire tangential width of blocks (0.7-1.1 cms) was seven per cent. For an accuracy of ± 1 per cent in mean proportional area a ten per cent error in estimation was allowable. Using the expression (3.1) on the data, one traverse on each tangential surface was found adequate.

(b) Percentage Vessels and Fibres by Volume

These parameters were determined on the traverse surface where the surface area visible is equivalent to the volume occupied

by the tissue in the block as the vessels can be considered as continuous vertical cylinders.

As percentage rays had already been estimated the sample was orientated so that the traverse was parallel to the rays thus passing mainly over non-ray material. An error is introduced where the traverse intersects rays which are looped around vessels (Plate 3.4) but the length of traverse occupied by these intercepts compared to the total traverse length was negligible.

The results for percentage vessels and fibres were corrected to allow for ray percentage in the manner given in Table 3.4.

3.7 NUMBER OF VESSELS PER UNIT AREA OF CROSS-SECTION

Vessels may have a bearing on density in this species because of their large size (Plate 3.1A).

The unit quadrat was fixed at four square millimeters (two-millimeter square inscribed on a sheet of clear acetate). By keeping the same sample area, precision varied depending on vessel size and density (counts ranged from 15 to 150 per quadrat). An error of 13 per cent ($\pm$ approximately three vessels/square mm) was accepted for dense, small vessels necessitating eight quadrat units be counted per sample. With larger, less numerous vessels, an error of ten per cent ($\pm$ one vessel/sq mm) was acceptable necessitating four quadrat units per sample. These values were calculated as shown earlier using the normal deviate $t = 1.96$ for 95 per cent confidence level (Figure 3.5).

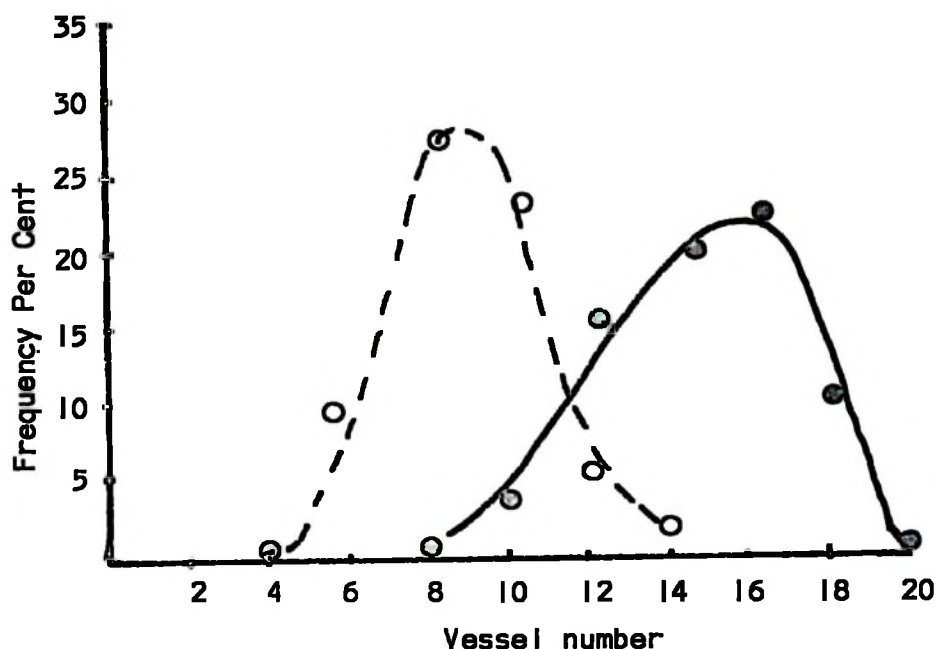


FIGURE 3.5 Vessel number distribution. Broken line for vessels at 85 per cent distance from the pith. Unbroken line for vessels at five per cent distance from pith.

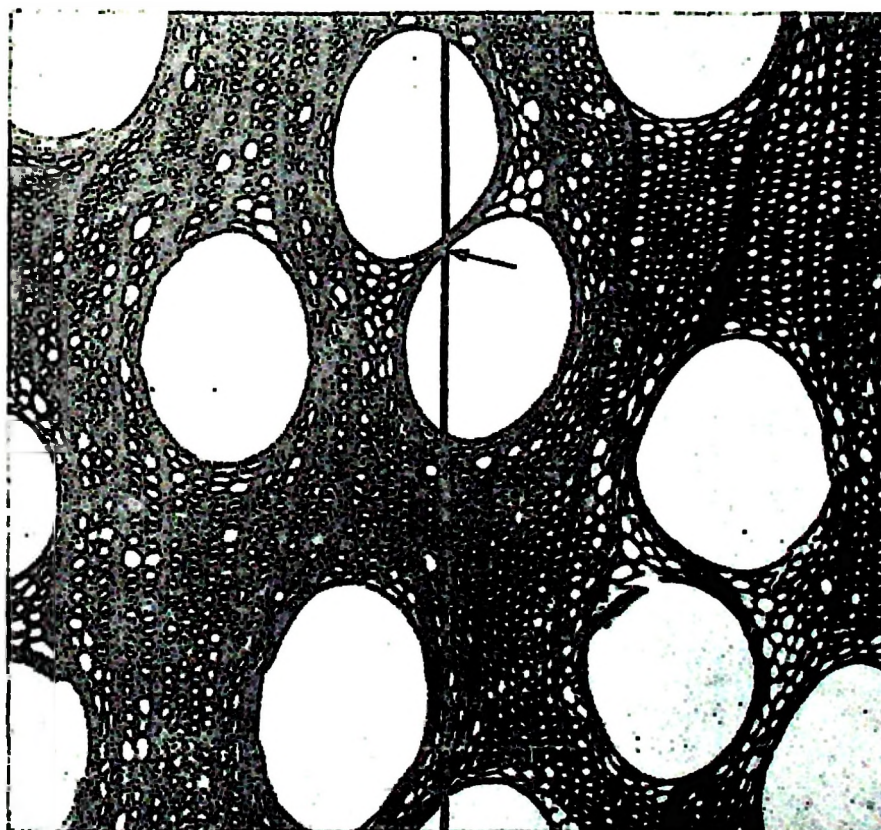


PLATE 3.4 Small errors occur in the summation of fibres and vessels when the traverse (black line) crosses a ray (arrowed) where it loops round a vessel. Theoretically, the traverse should move parallel to the rays without crossing them (see Table 3.4, p. 63).

TABLE 3.4 METHOD FOR CALCULATION OF PERCENTAGE BY VOLUME OF TISSUE TYPES IN WOOD BLOCKS

	Uncorrected result	Correction factor	Corrected result
On the tangential surface:			
$\frac{\text{Length of ray traverse}}{\text{Length of non-ray traverse}} \times \frac{100}{1}$	=	(no correction required)	= % rays
On the transverse surface:			
$\frac{\text{Length of vessel traverse}}{\text{Length of total traverse}} \times \frac{100}{1}$	=	% vessels $\times \frac{100 - \% \text{ rays}}{100}$	= % vessels
$\frac{\text{Length of fibre traverse}}{\text{Length of total traverse}} \times \frac{100}{1}$	=	% fibres $\times \frac{100 - \% \text{ rays}}{100}$	= % fibres
	$\frac{100}{100}$		$\frac{100}{100}$

3.8 MEAN CROSS-SECTIONAL AREA OF VESSELS

As radial and tangential measurements of vessels would have been difficult and tedious, mean cross-sectional area of vessels was accepted as an index of vessel size.

This parameter was determined by dividing percentage volume of wood occupied by vessels (equal to percentage area of vessels appearing on unit area cross-section) obtained in Section 3.6 (b) by number of vessels per unit area obtained in Section 3.7.

3.9 TOTAL EXTRACTIVES

The presence, distribution and nature (physical and chemical) of extraneous materials in wood may markedly affect its end use properties and density. Extraneous materials include calcium salts, kinos (phenolic substances), silica, gums, resins, fats, waxes, oils, tannins, starch, alkaloids, volatile substances and colouring matter. Those which can be removed with various solvents are termed extractives. Commonly used solvents include alcohol (removes tannins), alcohol-benzene solution (removes resins, oils, fats and waxes) and hot water (removes starch, salts and colouring matter).

In eucalypts the best method for removal and estimation of extractives is the appropriate Appita Standard P5m 61 'Solubility of wood in boiling tenth normal sodium hydroxide' (Hillis, 1969, personal communication). Materials which are soluble in boiling dilute sodium hydroxide include tannins, kinos and colouring matter.

This method also removes small amounts of carbohydrate material and lignin. The amount of lignin removed is insignificant in a study of this type (Hillis, 1969, personal communication). No detailed studies of the amount of carbohydrate material removed by dilute alkali have been made. The results obtained are arbitrary and governed by the way in which the method is applied. Any departure from the prescribed conditions may change the nature and amount of material extracted.

The analyses were carried out on duplicate samples. The duplicate results were required to agree within 0.5 per cent and the mean solubility of the wood in boiling tenth normal sodium hydroxide was recorded to the nearest 0.1 per cent.

3.10 LIGNIN

Lignin is a complex aromatic compound which is deposited in the cell walls of vessels and fibres conferring on them strength and rigidity. Some 25-30 per cent of the wood of eucalypts is lignin material.

Lignin was determined by a modified Tappi Standard Method T13 m -54 (ASTM Designation: D1106-56). The modification involved deleting the section referring to pre-extraction with benzene-alcohol as this has been found unsuitable for treatment of eucalypts (Hillis, personal communication) and substituting a pre-extraction with dilute alkali as described in Section 3.9 above.

The principle of this method is that the extractive free wood is treated with strong (72 per cent) sulphuric acid, hydrolyzing the carbohydrates and leaving an insoluble residue which is determined as lignin. If the pre-extraction is not used on eucalypt wood the standard sulphuric acid method will give inflated

results as co-precipitation of phenolic substances will occur with the lignin. However, with pre-extraction the lignin value may be slightly understated because of the removal of a small amount of lignin by the dilute alkali as already mentioned.

Some lignin may also remain in the acid solution and this is difficult to determine (Bland and Menshun, 1971).

Despite possible inaccuracies in the method for absolute lignin determination the modified standard was acceptable for comparative purposes in this study. Acid insoluble lignin was recorded on a dry weight unextracted wood basis and was not corrected for ash as fritted-glass crucibles were used.

3.11 CRUDE YIELD

After removal of extractives and lignin the material remaining may be termed 'holo cellulose' or 'total carbohydrate fraction' (Cohen and Dadswell, 1939). However, as some carbohydrate material may have been removed along with the extractives fraction, the author has adopted the term crude yield to describe the fraction $[(100 - \text{dilute alkali soluble extractives} - \text{concentrated sulphuric acid insoluble lignin}) \text{ percent}]$.

The methods described in this Chapter were used to determine associations between parameters measured on a number of small wood blocks.

CHAPTER 4

ASSOCIATIONS BETWEEN MEASURED WOOD PARAMETERS

4.1 INTRODUCTION

In the previous Chapter, the principles and precision of measurement of a large number of variables, which could be used to characterize an individual wood sample, were described. Some variables were included because they were easy to measure and it was hoped they would yield some important information about the wood sample, others were very difficult or tedious to measure and were included because other investigators' results indicated that they could be important. Many of the variables are inherently inter-related and, in this Chapter, this complex data situation is analysed.

4.2 EXPERIMENTAL MATERIAL

A total of 486 wood blocks (each about 1 cc. in volume) were removed from nine felled plantation-grown *Eucalyptus deglupta* trees, 19 years of age at Keravat, New Britain.

To integrate possible within-tree sampling effects, nine heights (ground level, breast height, 10, 20, 30, 40, 50, 60 and 70 per cent of final tree height) and six pith-to-bark positions (5, 25, 45, 65, 85 and 95 per cent of final radius from pith) were sampled, i.e.,

$$\begin{array}{rcccccccl} \text{trees} & \times & \text{heights} & \times & \text{radii} & = & \text{total} \\ 9 & \times & 9 & \times & 6 & = & 486 \end{array}$$

4.3 EXPERIMENTAL METHOD

The variables were measured as described in Chapter 3. The variables may be classified as 'primary', if measured on the sample directly, or 'derived' if calculated from combinations of primary measurements or from an assumed model for fibre cross-sectional shape (Table 4.1).

4.4 RESULTS

The result from this study was a data matrix, consisting of a two dimensional array of 486 individuals by 24 variables; too large to be presented in full. The individuals represented the wood blocks under study and the variables the measured parameters. This information was transferred to punched cards for computer analysis.

4.5 ANALYSIS

The use of pre-conceived ideas to reduce the quantity of this data was considered undesirable as this would have involved subjective selection. Subjective decisions were made as to parameters to be measured in the time available but sampling and measurement procedure were fundamentally objective, and the techniques used allowed estimates within certain limits of precision to be made.

TABLE 4.1 CLASSIFICATION AND IDENTIFICATION OF VARIABLES

Primary

- *1. Fibre length (FL)
- 2. Fibre double-wall thickness (2W)
- 3. Fibre lumen diameter (L)
- 5. Proportion of rays by volume (RV)
- 6. Proportion of fibres and vertical parenchyma by volume (FV)
- 7. Proportion of vessels by volume (VV)
- 8. Number of vessels per unit area of cross-section (VNO)
- 22. Percentage lignin by weight (LIG)
- 23. Percentage extractives by weight (EXT)

Derived

- 4. Fibre diameter (2 + 3) (D)
- 9. Vessel cross-sectional area (vessel size) (from 7 and 8) (VS)
- 10. Felting coefficient. Fibre length/diameter ratio (from 1 and 4) (FL/D)
- 11. Runkel Ratio. Ratio double wall thickness/lumen diameter (from 2 and 3) (2W/L)
- 12. Isenberg coefficient. Ratio wall thickness/fibre diameter (from 2 and 4) (2W/D)
- 13. Flexibility coefficient ratio fibre lumen diameter/fibre diameter (from 3 and 4) (L/D)
- 14. Number of fibres per unit length of radial traverse (reciprocal of 4) (FIBS)
- 15. Cross-sectional area of fibre wall material (from 2 and 3 through a model developed in Chapter 3) (WA)
- 16. Cross-sectional area of fibre (from 2 and 3 through model) (FA)
- 17. Cross-sectional area of fibre lumen (from difference between 15 and 16) (LA)
- 18. Ratio cross-sectional area of fibre wall material/cross-sectional area of fibre (Mulsteph Coefficient) (from 15 and 16) (WA/FA)
- 19. Ratio cross-sectional area of fibre lumen/cross-sectional area of fibre (from 16 and 17) (LA/FA)
- 20. Ratio cross-sectional area of fibre lumen/cross-sectional area of fibre wall material (from 15 and 17) (LA/WA)
- 21. Number of fibres per unit area of cross-section (Reciprocal of 16) (FIBS/A)
- 24. Percentage crude yield (holocellulose) by weight [100 per cent - (22 + 23)] (HOL0)

*The numbers opposite each parameter will be used for subsequent reference to the parameter as a subscript of an x variable; e.g., x_2 will refer to fibre double-wall thickness.

The data structure was investigated to ascertain whether the variables closely approximated the normal distribution. This was done to ensure the statistical techniques used later in data analysis could be applied with confidence. The data was examined using programme SCREEN (Appendix 5). A sample of the dispersion statistics obtained has been presented in Table 4.2 using one tree as an example. The Kolmogorov-Smirnov test for goodness of fit (Sokal and Rohlf, 1969) indicates, at the five per cent probability level, there is little evidence to reject the null hypothesis that the parameter measurements are normally distributed. Transformation of the data was, therefore, not required.

The degree of association between variables or the degree to which they vary together was examined by computing product-moment correlation coefficients between all possible pairs. The correlation matrix with standard errors is given in Table 4.3. This matrix is more compact than the data matrix and solves the problem of different units and scales in the variables. The statistical significance of the association between any pair of variables can be ascertained by reference to tables of values of the correlation coefficient for different levels of significance such as those in Fisher and Yates (1953). The levels of significance are indicated by the asterisks in Table 4.3

Of the 300 correlation coefficients, 229 are significant at the 0.1 per cent level. This large number of high correlations could result from the many degrees of freedom or because individual correlations between any two variables

TABLE 4.2 DISPERSION STATISTICS FOR MEASURED VARIABLES - TREE NUMBER ONE

Variable Units of Measurement	Mean			Median			Variance Standard Deviation			Coefficient of Variation per cent			Skewness			Kurtosis			Kolmogorov-Smirnov Statistic				
	Value Standard Error			Value Standard Error			Value Standard Error			Value Standard Error			Value Standard Error			Value Standard Error							
	95 per cent confidence limits	lower	upper	95 per cent confidence limits	lower	upper	95 per cent confidence limits	lower	upper	95 per cent confidence limits	lower	upper	95 per cent confidence limits	lower	upper	95 per cent confidence limits	lower	upper					
μ_1 mm	0.994	0.025	0.943	1.045	0.032	1.001	1.129	0.035	0.187	18.79	1.87	15.03	22.54	-0.72	0.32	-1.36	-0.09	-0.67	0.64	-1.92	0.58	0.149 [#]	
μ_2 microns	5.4	0.2	5.1	5.7	5.0	0.2	4.6	5.4	0.001	0.116	21.63	2.18	17.25	26.00	0.91	0.32	0.27	1.54	0.29	0.64	-0.66	1.84	0.146
μ_3 microns	7.9	0.2	7.6	8.2	7.8	0.2	7.4	8.2	0.001	0.116	14.66	1.44	11.77	17.55	-0.21	0.32	-0.85	0.42	0.18	0.64	-1.07	1.43	0.105
μ_4 microns	13.3	0.2	12.9	13.7	13.1	0.3	12.6	13.6	0.002	0.149	11.22	1.09	9.03	13.41	0.33	0.32	-0.31	0.96	0.25	0.64	-1.00	1.51	0.087
μ_5 per cent	18.5	0.3	18.0	19.1	18.0	0.3	17.3	19.1	4.18	2.04	19.40	1.94	15.51	23.28	0.86	0.32	0.22	1.50	0.06	0.64	-1.20	1.31	0.137
μ_6 per cent	63.5	0.7	62.2	64.8	63.6	0.8	62.0	65.3	23.8	4.88	7.68	0.74	6.19	9.18	-0.30	0.32	-0.84	0.33	-0.61	0.64	-1.86	0.65	0.078
μ_7 per cent	27.9	1.2	25.6	30.3	25.0	1.5	22.0	27.9	74.2	8.61	30.81	3.23	24.33	37.30	0.73	0.32	0.09	1.36	-0.22	0.64	-1.47	1.04	0.169
μ_8 number/mm ²	9.3	0.3	8.7	9.9	8.7	0.4	8.0	9.4	4.4	2.09	22.45	2.26	17.91	27.00	1.33	0.32	0.69	1.97	1.90	0.64	0.66	3.16	0.149
μ_9 m ²	0.029	0.001	0.027	0.031	0.029	0.001	0.026	0.031	0.0001	0.009	30.08	3.15	23.77	36.39	-0.01	0.32	-0.65	0.62	-0.57	0.64	-1.82	0.66	0.049
μ_{10} ratio	7.45	1.5	71.5	77.5	74.9	1.9	71.1	78.7	121.4	11.07	14.79	1.45	11.87	17.7	-0.21	0.32	-0.85	0.42	-0.47	0.64	-1.72	0.78	0.097
μ_{11} ratio	0.708	0.034	0.633	0.769	0.616	0.043	0.531	0.701	0.082	0.249	35.58	3.85	27.89	43.26	3.03	0.32	2.40	3.67	13.46	0.64	12.21	14.71	0.161
μ_{12} ratio	0.402	0.009	0.394	0.421	0.382	0.012	0.358	0.405	0.005	0.068	16.91	1.67	13.56	20.27	1.36	0.32	0.72	1.99	3.32	0.64	2.07	4.58	0.134
μ_{13} ratio	0.595	0.009	0.578	0.615	0.619	0.011	0.596	0.642	0.005	0.067	11.24	1.10	9.05	13.44	-1.41	0.32	-2.05	-0.77	3.32	0.64	2.36	4.77	0.130
μ_{14} number/mm	76.1	1.2	73.7	78.4	76.3	1.5	73.4	79.2	7.30	8.56	11.25	1.10	9.00	13.46	0.41	0.32	-0.23	1.04	0.62	0.64	-0.64	1.87	0.091
μ_{15} microns ²	99.3	3.7	91.8	106.7	100.0	4.6	90.7	109.3	74.3	8.62	27.46	2.83	21.77	33.14	0.82	0.32	0.18	1.45	0.47	0.64	-0.78	1.72	0.174
μ_{16} microns ²	155.9	4.7	146.4	165.4	150.0	5.9	136.1	161.9	120.9	11.08	22.30	2.25	17.79	26.82	0.67	0.32	0.03	1.31	0.55	0.64	-0.71	1.80	0.142
μ_{17} microns ²	55.9	2.2	51.5	60.3	50.0	2.8	44.3	59.5	26.2	5.1	28.96	3.01	22.82	35.08	0.20	0.32	-0.44	0.84	-0.30	0.64	-1.36	0.73	0.180
μ_{18} ratio	0.639	0.010	0.618	0.659	0.618	0.013	0.592	0.643	0.006	0.075	11.75	1.15	9.45	14.05	0.84	0.32	0.21	1.48	1.27	0.64	0.02	2.53	0.129
μ_{19} ratio	0.596	0.004	0.557	0.634	0.630	0.030	0.560	0.681	0.031	0.177	30.24	3.16	23.89	36.58	-0.11	0.32	-0.71	0.52	0.02	0.64	-1.23	1.27	0.095
μ_{20} ratio	0.361	0.010	0.341	0.382	0.383	0.013	0.357	0.408	0.006	0.075	20.77	2.08	16.99	24.94	-0.84	0.32	-1.48	-0.20	1.27	0.64	0.02	2.53	0.111
μ_{21} number/mm ²	67.1	1.93	63.2	71.0	67.0	2.4	62.2	71.8	201.0	14.2	21.13	2.12	16.87	25.38	0.43	0.32	-0.21	1.07	0.07	0.64	-1.18	1.32	0.099
μ_{22} per cent	23.5	0.6	22.4	24.6	23.0	0.7	21.6	24.4	16.5	4.1	17.29	1.71	13.85	20.72	0.66	0.32	0.03	1.30	-0.29	0.64	-1.54	0.97	0.115
μ_{23} per cent	17.5	0.2	17.0	17.9	17.7	0.3	17.1	18.3	2.9	1.7	9.79	0.95	7.89	11.70	-0.09	0.32	-0.72	0.55	-0.56	0.64	-1.81	0.69	0.081
μ_{24} per cent	59.1	0.7	57.7	60.5	60.6	0.9	59.0	62.6	26.3	5.1	8.7	0.8	7.0	10.4	-0.85	0.32	-1.48	-3.21	0.26	0.64	-0.99	1.52	0.131

#The critical value of the Kolmogorov-Smirnov Statistic = 0.181 at the five per cent probability level.

within the body of the table may not be wholly the result of causal effects of one on the other, but due to the effects of position within the tree on both. The observed correlation between the variables could occur under any of the situations depicted in Table 4.4.

The correlation matrix is thus limited, as a means of interpreting and understanding the data, but serves as a base for other statistical techniques.

In geometric terms each variable measured is an axis, all mutually at right angles (orthogonal) and individual values are fixed in multidimensional space by their values along the variable axes. This results in clouds of observations describing hyper-ellipsoids in multi-dimensional space which may be difficult to visualise. The structure of this space of more than three dimensions can be determined objectively by reconstructing the movement of the variables from a small number of common factors or components. The latter are not themselves observed, but are constructed with a view to explaining the observed variables.

Methods of principal component analysis (PCA) and factor analysis (FA) were originally developed and applied largely by psychologists. They were used for analysing the structure of abilities reflected in batteries of mental tests, and various procedures have been suggested and applied by different workers (e.g., Cooley and Lohnes, 1962; Harmon, 1960). These systems are being used increasingly to understand complex systems in nature (e.g., Cassie, 1963; Cassie and Michael, 1968; Norris, 1970) but to the author's knowledge have not been used in published wood quality studies. The PCA method is outlined in Appendix 2 and results are presented in Table 4.5.

TABLE 4.4 SOME POSTULATED MODELS EXPLAINING THE OBSERVED CORRELATION (r_{12}) BETWEEN TWO VARIABLES x_1 AND x_2 , ASSUMING LINEAR RELATIONSHIPS BETWEEN VARIABLES

MODEL	COMMENTS
1. $x_1 \longleftarrow x_2$	One variable completely affects the variation in the other. $r_{12} = 1.0$.
2. $\begin{array}{c} x_1 \swarrow \\ x_2 \swarrow \end{array} x_3$	Variables x_1 and x_2 are totally determined by a single common effect x_3 . $r_{12} = 1.0$.
3. $\begin{array}{c} x_1 \longleftarrow x_3 \\ \uparrow \\ x_2 \end{array}$ e.g. x_1 = fibre diameter x_2 = distance from pith x_3 = lumen diameter	x_2 is one of two variables affecting x_1 . $r_{12} < 1$.
4. $\begin{array}{c} x_1 \longleftarrow x_3 \\ \uparrow \quad \swarrow \\ x_2 \quad x_4 \end{array}$ e.g. x_1 = fibre diameter x_2 = distance from pith x_3 = fibre lumen diameter x_4 = fibre wall thickness	x_2 , x_3 and x_4 are separately affecting x_1 . $r_{12} < 1$. A partial correlation $< r$ would suggest x_3 and x_4 both have an effect on the correlation of x_1 and x_2

TABLE 4.4 CONT.

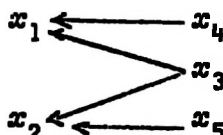
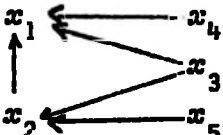
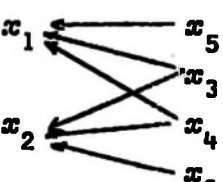
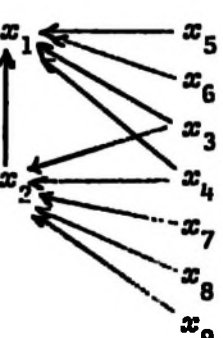
MODEL	COMMENTS
5.  e.g. x_1 = fibre wall thickness x_2 = fibre diameter x_3 = distance from pith x_4 = fibre length x_5 = lumen diameter	The correlation between x_1 and x_2 is due to a common effect of x_3. Correlation r_{12} is not perfect because of separate effects of x_4 and x_5 on x_1 and x_2 respectively.
6.  e.g. examples in model 5 could be used	The correlation between x_1 and x_2 is due to the direct effect of x_2 on x_1 as well as the common effect x_3. Other effects x_4 and x_5 combine to reduce the significance of r_{12}.
7. 	The correlation between x_1 and x_2 is due to two common effects x_3 and x_4. r_{12} is reduced by effects of x_5 and x_6.
8. 	Obviously models of increasing complexity can be drawn, any of which could occur in the type of data obtained in this study. Subjective methods are of little use in unravelling this type of structure.

TABLE 4.5 RESULTS OF PRINCIPAL COMPONENTS ANALYSIS ON THE MEASURED PARAMETERS

Component or eigen vector number	1 (ξ_1)	2 (ξ_2)	3 (ξ_3)	4 (ξ_4)
Eigen values	14.05 (λ_1)	4.52 (λ_2)	2.85 (λ_3)	1.01 (λ_4)
Cumulative percentage of eigen values	58.5	77.4	89.3	93.5
Percentage of total eigen values in each component	58.5	18.8	11.9	4.2
Variables and their eigen vector coefficients (α)	$x_2(2W)+0.26$ $x_{15}(WA)+0.26$ $x_{16}(FA)+0.25$ $x_{18}(WA/FA)+0.25$ $x_{12}(2W/D)+0.25$	$x_9(VS)+0.45$ $x_7(VV)+0.34$ $x_{10}(FL/D)+0.31$ $x_{24}(HOLO)+0.27$ $x_1(FL)+0.26$	$x_{17}(LA)+0.52$ $x_3(L)+0.51$ $x_{10}(FL/D)+0.24$ $x_1(FL)+0.21$ $x_4(D)+0.17$	$x_{10}(FL/D)+0.56$ $x_5(RV)+0.33$ $x_1(FL)+0.33$ $x_{14}(FIBS)+0.19$ $x_{21}(FIBS/A)+0.14$
(Meaning of bold type is explained in the text)	$x_{11}(2W/L)+0.25$ $x_4(D)+0.24$ $x_{23}(EXT)+0.21$ $x_{22}(LIG)+0.19$ $x_6(FV)+0.17$ $x_1(FL)+0.17$ $x_5(RV)+0.12$ $x_{10}(FL/D)+0.05$ $x_9(VS)-0.04$ $x_{17}(LA)-0.05$ $x_3(L)-0.06$ $x_7(VV)-0.16$ $x_8(VNO)-0.18$ $x_{24}(HOLO)-0.19$ $x_{14}(FIBS)-0.23$ $x_{19}(LA/FA)-0.24$ $x_{21}(FIBS/A)-0.24$ $x_{20}(LA/WA)-0.25$ $x_{13}(L/D)-0.25$	$x_{18}(WA/FA)+0.09$ $x_{12}(2W/D)+0.08$ $x_4(D)+0.06$ $x_2(2W)+0.06$ $x_{16}(FA)+0.06$ $x_{15}(WA)+0.05$ $x_{11}(2W/L)+0.04$ $x_{17}(LA)+0.03$ $x_3(L)-0.00$ $x_{13}(L/D)-0.08$ $x_{14}(FIBS)-0.09$ $x_{20}(LA/WA)-0.09$ $x_{21}(FIBS/A)-0.11$ $x_{19}(LA/FA)-0.12$ $x_8(VNO)-0.21$ $x_{23}(EXT)-0.25$ $x_{22}(LIG)-0.27$ $x_6(FV)-0.29$ $x_5(RV)-0.33$	$x_{19}(LA/FA)+0.16$ $x_{20}(LA/WA)+0.16$ $x_{13}(L/D)+0.16$ $x_{22}(LIG)+0.14$ $x_{16}(FA)+0.11$ $x_{23}(EXT)+0.08$ $x_9(VS)+0.05$ $x_{15}(WA)+0.01$ $x_6(FV)-0.05$ $x_2(2W)-0.05$ $x_7(VV)-0.07$ $x_{24}(HOLO)-0.13$ $x_{14}(FIBS)-0.14$ $x_{12}(2W/D)-0.16$ $x_{18}(WA/FA)-0.16$ $x_{21}(FIBS/A)-0.16$ $x_{11}(2W/L)-0.17$ $x_8(VNO)-0.18$ $x_5(RV)-0.20$	$x_{22}(LIG)+0.14$ $x_{23}(EXT)+0.11$ $x_{13}(L/D)+0.02$ $x_9(VS)+0.01$ $x_{20}(LA/WA)+0.00$ $x_{18}(WA/FA)-0.00$ $x_{12}(2W/D)-0.01$ $x_{19}(LA/FA)-0.01$ $x_{11}(2W/L)-0.04$ $x_6(FV)-0.09$ $x_7(VV)-0.11$ $x_2(2W)-0.11$ $x_{24}(HOLO)-0.14$ $x_{15}(WA)-0.17$ $x_{16}(FA)-0.20$ $x_8(VNO)-0.22$ $x_4(D)-0.24$ $x_{17}(LA)-0.24$ $x_3(L)-0.29$

In this Table, the four columns, called components, are statistically uncorrelated. The eigen values for each component represent the proportion of the total variance of all parameters in the system which can be assigned to each component. Components 1-4 represent 58.5, 18.8, 11.9 and 4.2 per cent or a total of 93.5 per cent of the total variance in the data. Therefore, nearly all of the variance in the data system of 24 variables has been accounted for by only four new variables or components. The first two components alone account for 77.4 per cent of the variance in the system.

In the lower part of Table 4.5 are four columns of scores (coefficients), one for each variable. These columns are termed the component or eigen vectors. In the interpretation of components, absolute values of the eigen vector coefficients are not of primary importance, but relative magnitudes and signs are. The vectors have been arranged so that the larger positive coefficients are at the top and the larger negative scores are at the bottom (i.e., the components are made bi-polar). Coefficients of the same magnitude, irrespective of sign, have the same degree of significance within the component, so that, in the first component, for example, double wall thickness (x_2), fibre area (x_{16}), fibre diameter (x_4), wall area (x_{15}), number of fibres/unit area (x_{21}), number of fibres in unit radial file (x_{14}) and several ratios (x_{18} , x_{12} , x_{11} , x_{19} , x_{21} , x_{20} , x_{13}) have approximately similar coefficients but the signs indicate complementary features in the relationship. For example, if fibre area (x_{16}) (+ sign) is increased, the number of fibres per unit area of cross-section (x_{21}) (- sign) decreases.

As explained in Appendix 2, there are four expressions giving the new variables (ξ) in terms of the measured variables (x). The first is

$$\begin{aligned}\xi_1 = & 0.17x_1 + 0.26x_2 - 0.06x_3 + 0.24x_4 + 0.12x_5 \\ & + 0.17x_6 - 0.16x_7 - 0.18x_8 - 0.04x_9 + 0.05x_{10} \\ & + 0.25x_{11} + 0.25x_{12} - 0.25x_{13} - 0.23x_{14} \\ & + 0.26x_{15} + 0.25x_{16} - 0.05x_{17} + 0.25x_{18} \\ & - 0.24x_{19} - 0.25x_{20} - 0.24x_{21} + 0.19x_{22} \\ & + 0.21x_{23} - 0.19x_{24}\end{aligned}$$

the coefficients of x being the eigen vector coefficients from Table 4.5. The other three equations for ξ_2 , ξ_3 and ξ_4 can be constructed similarly. These equations are exact if all the x variables are included. They are approximations (regression equations) if only the important (large coefficients) variables are included. For example

$$\begin{aligned}\xi_1 = & 0.26x_2 + 0.24x_4 + 0.25x_{11} + 0.25x_{12} - 0.25x_{13} \\ & - 0.23x_{14} + 0.26x_{15} + 0.25x_{16} + 0.25x_{18} \\ & - 0.24x_{19} - 0.25x_{20} - 0.24x_{21} + 0.19x_{22} \\ & + 0.21x_{23} - 0.19x_{24} + \epsilon\end{aligned}$$

where ϵ is a term representing the residual variables. This is ignored as it is small in relation to the other terms in the equation.

If the new variables (ξ) are standardised to unit variance during factor analysis (Appendix 3) the vector coefficients become

the correlation coefficients between the measured variables and the factors (F). The four factors which fit the data are given in Table 4.6.

It is difficult to determine which coefficients are important, especially in the first factor where there are several values between ± 0.60 and ± 0.80 . These values can be given more meaning by the use of a varimax rotation (Appendix 3) which rotates the axes to which the measured parameters are referenced so that the set of factors account for as much of the total system variance as possible (hence 'varimax') (Kaiser, 1958). The rotated factor matrix is given in Table 4.7.

Its effect can be judged by looking at variables x_{22} (LIG), x_{23} (EXT) and x_{24} (HOL0). In the non-rotated factor analysis (Table 4.6) they are apparently important ($+0.73$, $+0.78$, -0.73 respectively) but the rotated factor analysis suggests this apparent importance was not real because the coefficients have been markedly reduced ($+0.39$, $+0.47$, -0.40 respectively). The coefficients of variables such as x_4 (D), x_2 (2W), x_{12} (2W/D), x_{11} (2W/L), x_{13} (L/D), x_{14} (FIBS), x_{15} (WA), x_{16} (FA), x_{18} (WA/FA), x_{19} (LA/FA), x_{20} (LA/WA) and x_{21} (FIBS/A) have not been affected. Similar reasoning can be made on the other three factors.

The factor information can then be used to ascertain which variables feature prominently in the original components. The important variables have been emphasized in Table 4.5 by the use of bold type.

TABLE 4.6 RESULTS OF A FACTOR ANALYSIS ON THE MEASURED PARAMETERS
(CONFORMING TO THE FOUR-COMPONENT-MODEL GIVEN IN
TABLE 4.5)

VARIABLES	FACTORS			
	1 (F ₁)	2 (F ₂)	3 (F ₃)	4 (F ₄)
x_1 (FL)	+0.64	+0.54	+0.36	+0.33
x_2 (2W)	+0.96	+0.13	-0.08	-0.11
x_3 (L)	-0.24	-0.01	+0.86	-0.29
x_4 (D)	+0.89	+0.12	+0.28	-0.24
x_5 (RV)	+0.44	-0.71	+0.33	+0.34
x_6 (FV)	+0.65	-0.62	-0.09	-0.09
x_7 (VV)	-0.61	+0.72	-0.11	-0.11
x_8 (VNO)	-0.69	-0.44	-0.30	-0.23
x_9 (VS)	-0.19	+0.95	+0.08	+0.02
x_{10} (FL/D)	+0.20	+0.66	+0.41	+0.56
x_{11} (2W/L)	+0.94	+0.08	-0.29	-0.04
x_{12} (2W/D)	+0.94	+0.16	-0.28	-0.01
x_{13} (L/D)	-0.95	-0.16	+0.27	+0.02
x_{14} (FIBS)	-0.87	-0.19	-0.24	+0.19
x_{15} (WA)	+0.96	+0.11	+0.02	-0.17
x_{16} (FA)	+0.93	+0.12	+0.19	-0.21
x_{17} (LA)	-0.20	+0.06	+0.88	-0.24
x_{18} (WA/FA)	+0.94	+0.20	-0.27	-0.00
x_{19} (LA/FA)	-0.91	-0.25	+0.27	-0.01
x_{20} (LA/WA)	-0.94	-0.20	+0.27	+0.00
x_{21} (FIBS/A)	-0.90	-0.24	-0.27	0.15
x_{22} (LIG)	+0.73	-0.58	+0.23	0.14
x_{23} (EXT)	+0.78	-0.52	+0.14	0.11
x_{24} (HOL0)	-0.73	+0.56	-0.22	-0.14

The factors F_{1-4} correspond to the four components ξ_{1-4} in Table 4.5.

$$F_i = \xi_i \cdot \lambda^{-0.5}$$

The figures in the body of the table are factor vector (correlation) coefficients (f).

TABLE 4.7 RESULTS OF FACTOR ANALYSIS AND VARIMAX ROTATION ON THE MEASURED PARAMETERS (CONFORMING TO THE FOUR-COMPONENT-MODEL GIVEN IN TABLE 4.5)

VARIABLES	FACTORS			
	1 (F ₁)	2 (F ₂)	3 (F ₃)	4 (F ₄)
x_1 (FL)	+0.59	+0.00	+0.10	+0.76
x_2 (2W)	+0.93	-0.26	-0.15	+0.10
x_3 (L)	-0.15	-0.00	+0.92	+0.07
x_4 (D)	+0.90	-0.28	+0.24	+0.13
x_5 (RV)	+0.03	-0.95	+0.07	+0.14
x_6 (FV)	+0.41	-0.74	-0.14	-0.28
x_7 (VV)	-0.26	+0.92	+0.05	+0.10
x_8 (VNO)	-0.65	+0.07	-0.08	-0.62
x_9 (VS)	+0.13	+0.85	+0.11	+0.46
x_{10} (FL/D)	+0.16	+0.20	+0.10	+0.93
x_{11} (2W/L)	+0.88	-0.26	-0.36	+0.05
x_{12} (2W/D)	+0.90	-0.21	-0.37	+0.12
x_{13} (L/D)	-0.90	+0.21	+0.36	-0.11
x_{14} (FIBS)	-0.87	+0.22	-0.18	-0.18
x_{15} (WA)	+0.94	-0.28	-0.04	+0.09
x_{16} (FA)	+0.92	-0.29	+0.13	+0.13
x_{17} (LA)	-0.12	+0.01	+0.92	+0.15
x_{18} (WA/FA)	+0.90	-0.18	-0.36	+0.14
x_{19} (LA/FA)	-0.88	+0.13	+0.36	-0.17
x_{20} (LA/WA)	-0.90	+0.18	+0.36	-0.14
x_{21} (FIBS/A)	-0.90	+0.21	-0.19	-0.26
x_{22} (LIG)	+0.39	-0.89	+0.04	+0.06
x_{23} (EXT)	+0.47	-0.83	-0.04	+0.03
x_{24} (HOLO)	-0.40	+0.87	-0.03	-0.06

Values > 0.74 were used to ascertain the important members of the components in Table 4.5 (underlined and in bold type).

The figures in the body of the table are rotated factor vector (correlation) coefficients.

The 12 variables showing a good degree of association with the first component are all fibre cross-section parameters or their ratios. All are equally well correlated with the component (> 0.87 in Table 4.7), thus any one could determine the component.

There are seven variables showing a good degree of correlation with the second component. These include the three chemical constituents, lignin, extractives and holocellulose, proportional volumes of the three tissue types and vessel size.

The third component contains only two important variables concerning fibre lumen size.

Two variables, fibre length and fibre length/diameter ratio (felting coefficient), are featured in the fourth component.

To describe the variability in *E. deglupta* wood, any one of the variables underlined in the first principal component in Table 4.5 could be used to account for some 58 per cent of the total variation. Fibre double wall thickness ($x_2(2W)$) is the most useful variable by a very small margin. The fibre ratios such as the Runkel ratio and Isenberg coefficient developed by workers in the past in attempts to characterize wood for various end uses, feature prominently in the first component. Each could effectively describe 58 per cent of the variation in *E. deglupta* wood and are therefore useful parameters but inadequate to describe a major part of the variability.

To effectively describe more than 58 per cent of the wood variability one important variable in each component would need to be measured. For example fibre double wall thickness ($x_2(2W)$), vessel size ($x_9(VS)$) and fibre lumen diameter ($x_3(L)$) would describe close to 90 per cent of the wood variability.

In deciding which variables are suitable to use in practice, ease of measurement is important (Table 4.7). Of the important variables in the first three components, only number of fibres per unit length of radial traverse ($x_{14}(\text{FIBS})$) is relatively easy to determine. Vessel number per unit area ($x_8(\text{VNO})$), another variable readily determined in this species with its large vessels, does not feature prominently in any component. Similarly, fibre length is fairly easy to measure but only appears prominently in the fourth component describing only some four per cent of the wood variability. Hence vessel number and fibre length are of little practical use in characterizing the wood of *E. deglupta*.

Fibre length has nearly always been one of the parameters measured by researchers dealing with *Eucalyptus* wood quality. Some doubt now exists on the usefulness of fibre length as a significant parameter to describe *Eucalyptus* wood. However, this present study is based on nine trees of a tropical eucalypt. Similar studies are needed on other species, e.g., *E. regnans*, to determine whether the present results may be applied generally to fast grown eucalypts.

In summary the study, so far, has shown:

- I. Parameters of the wood of *E. deglupta* are inter-related in a complex way.
- II. Correlation analysis was found to be inappropriate to describe this inter-relationship.
- III. Suitable methods of describing the variation in the wood of *E. deglupta* were principal component analysis, factor analysis and varimax rotation.

TABLE 4.8 EASE AND PRECISION OF MEASUREMENT OF TWENTY-FOUR PARAMETERS MEASURED ON THE WOOD OF *E. DEGLUPTA*

Parameter ^o	Unit of Measurement	Ease of Measurement	Precision of Measurement* Per Cent of Mean	Precision as a Variable appears	Component [†] in which Variable appears
x ₁	mm	easy	± 0.032	3.0	4
x ₂	microns	difficult	± 0.5	7.7	1
x ₃	microns	difficult	± 0.5	6.3	3
x ₄	microns	difficult	± 0.5	3.5	1
x ₅	per cent	difficult	± 2.0	21.1	2
x ₆	per cent	difficult	± 5.0	7.6	2
x ₇	per cent	difficult	± 5.0	20.2	2
x ₈	No/mm ²	easy	± 2.0	24.1	-†
x ₉	mm ²	difficult	± 0.003	10.0	2
x ₁₀	ratio	-	-	-	4
x ₁₁	ratio	-	-	-	1
x ₁₂	ratio	-	-	-	1
x ₁₃	ratio	-	-	-	1
x ₁₄	No/mm	easy	± 2.0	2.4	1
x ₁₅	microns ²	difficult	± 16.0	12.7	1
x ₁₆	microns ²	difficult	± 13.0	7.2	1
x ₁₇	microns ²	difficult	± 7.0	12.5	3
x ₁₈	ratio	-	-	-	1
x ₁₉	ratio	-	-	-	1
x ₂₀	ratio	-	-	-	1
x ₂₁	No/mm ²	difficult	± 30.5	5.2	1
x ₂₂	per cent	difficult	± 0.5	2.1	2
x ₂₃	per cent	difficult	± 0.5	2.9	2
x ₂₄	per cent	difficult	± 0.5	0.9	2

^oA list of parameters is given in Table 4.1 on page 69.

*At 95 per cent confidence level

[†]See Table 4.5 on page 76.

+x₈ (Vessel number per unit area) did not feature prominently in any component.

- iv. The variation in wood of *E. deglupta* could be largely described by only four components representing 58.5, 18.8, 11.9 and 4.2 per cent of the total variation respectively.
- v. The first component consisted of fibre dimension parameters, particularly those describing the amount of wall material visible in cross-section.
- vi. The second component comprised vessel volume and size, volume of other tissues and chemical constituents.
- vii. The third component contained only two important variables concerning fibre lumen size.
- viii. The fourth component contained two parameters concerning fibre length.
- ix. Only 6.5 per cent of the total variability in samples of wood of *E. deglupta* remained unaccounted for in the four components.
- x. The chemical characters (lignin, extractives, holocellulose) vary independently from the fibre characters (because they appear in separate, components which are uncorrelated with each other).
- xi. Fibre length varies independently of fibre cross-sectional parameters except diameter and is a relatively unimportant variable in the wood of *E. deglupta*.
- xii. Fibre-wall thickness is the most useful single variable for describing the wood of *E. deglupta* but is difficult to measure.

- xiii. To describe better than 90 per cent of the variability in wood of *E. deglupta*, at least three parameters should be measured. One of these should come from among the prominent parameters in each of the first three components.
- xiv. Of the important variables in the first three components, only one (number of fibres per unit length of radial traverse) was relatively easy to measure.
- xv. Vessel number can be readily determined but does not feature prominently in any component and thus is not a useful parameter.

Provided a single parameter, which would be easy to measure and which would adequately describe more than one component, could be found, the task of describing the wood of *E. deglupta* could be much simplified.

It was decided to investigate the usefulness of wood density to describe variability in *E. deglupta* wood. In the next Chapter, several methods for measuring density are described. How well the density parameter describes the wood of *E. deglupta* is shown in Chapter 6.

CHAPTER 5

MEASUREMENT OF WOOD DENSITY

5.1 INTRODUCTION

Wood density is an easily determined property which provides a convenient single measure of the amount of material present. It is important in problems of handling and transportation, and in the yield of raw and processed materials as well as in properties and utilization of wood.

Density can be defined as the weight (in grams or pounds) of a measured volume (in cubic centimeters or cubic feet) of substance. In much of the literature and in wood technology the term specific gravity has been used. This can be defined as the ratio of the mass of unit volume of the material to the mass of a similar volume of water under the same conditions. The term specific gravity is often used in wood science even when the quantity actually determined is density as described previously.

Wood is a heterogeneous material and density measurement is complicated by the fact that wood volume changes in the presence of moisture. Thus, several measures of wood density can be made:

- i. oven-dry weight/oven-dry volume;
- ii. oven-dry weight/volume at specified moisture content;
- iii. air-dry weight/air dry volume;

- iv. air-dry weight/saturated volume;
- v. oven-dry weight/saturated volume;
- vi. weight at a specified moisture content/volume at the same specified moisture content.

To avoid shrinkage and other complications in trying to bring wood to a specified intermediate moisture content, it is usual to determine the weight of moisture-free wood (i.e., oven-dry and minimum volume conditions) and the volume in the saturated condition (i.e., maximum moisture, maximum volume conditions), the resulting weight/volume quantity being termed nominal specific gravity or basic density.

The need to make observations on samples in both saturated and dry conditions is time consuming as wood is difficult to saturate quickly and it is hard to judge when the saturated condition is reached. Wood is swollen to maximum volume at a moisture content little above fibre saturation point, i.e., before complete saturation. This is a distinct disadvantage compared with the procedure for stable, homogeneous compounds as complete saturation is needed to determine the volume of voids. Some of the other measures avoid this difficulty (e.g., I and III) and may be more immediately useful than basic density for specific purposes. Conversion from one measure to the other could be attempted provided data on dimensional changes with variation in moisture content were known (e.g., from density of air-dry or oven-dry wood to basic density).

Apart from the above gravimetric techniques a recent trend towards automation and the use of radio-isotopes has led to several radiation methods. These are usually calibrated to provide density values at some specified low moisture content.

5.2 GRAVIMETRIC METHODS

There are two common methods of determining basic density gravimetrically; the water-immersion and maximum moisture content methods. Details of these methods have been given by Smith (1954, 1955), Tappi (1963) and Phillips (1965).

(a) Basic density by water immersion method

Density by water immersion method (D_{WI}) is obtained through the following formula:

$$D_{WI} = \frac{W_o}{W_a - W_w}$$

where W_o = oven-dry weight of block in air

W_a = total saturated weight of block in air

W_w = weight of block while immersed in water

Derivation of this formula is explained in Appendix 4.

Only three weights are required. In this study the saturated weight in air (W_a) was obtained by suspending the saturated sample from the balance arm with pin and cotton. The saturated weight in water was obtained similarly with the specimen just submerged in a trough of water, on a bridge, over the balance pan. The pin was inserted into the specimen parallel to the grain to a constant depth, just sufficient to hold the sample. Care was needed to ensure that the block was completely submerged in the water and that the block and balance pan were not obstructed by the sides of

the trough or bridge. Oven dry weight was determined after drying the blocks for 48 hours in a vacuum oven at 85°C. This regime was accepted after preliminary tests which showed blocks reached a constant weight in about 36 hours. The usual precautions of transfer and cooling in desiccators were observed to prevent moisture being absorbed from the atmosphere.

(b) Basic density by maximum moisture content method

Density by maximum moisture content method (D_{MM}) was calculated as follows:

$$D_{MM} = \frac{W_o}{(W_a - W_o) + \frac{W_o}{1.53}}$$

where D_{MM} = basic density

W_o = oven dry weight

W_a = saturated weight in air

The quantity 1.53 (gms/cc) is the accepted value for the density of wood substance (Stamm, 1964).

The derivation of this formula is given in Appendix 4.

(c) Accuracy of gravimetric methods

Several methods of keeping the pin displacement constant by establishing the depth to which it is inserted in the block and how much pin is submerged in the water are presented by Keylwerth (1954), Smith (1955), Larson (1957) and others. However, no work dealing with the change in needle displacement and the measurement

error which ensues when the wood sample is submerged in water has been encountered in the literature. Sources of error in the determination of basic density in small wood samples by mercury displacement are given by Ericson (1966) and much of this applies in principle to water immersion methods but errors would be less because of the lower surface tension of water.

The condition of the wood surface is of great importance in determining the occurrence and magnitude of systematic errors. Surfaces should be smooth so that the water can adhere closely. Water adhering to saturated samples being weighed in air should be wiped away carefully. The magnitude of these errors is greater in small samples where the ratio of surface area to volume is greater than in larger samples (Table 5.1).

The apparent variation in cell wall density, arising largely from microscopic voids such as cell wall pits and membrane pores, (Ifju and Kennedy, 1962; Jayne and Krause, 1963; Ylannos, 1964) would not appear to invalidate the maximum moisture method which assumes a figure of 1.53 gms/cc for density of wood substance. These voids should fill with water in the maximum moisture method, especially when a vacuum is used to help extract air from these sites.

Differences due to chemical composition of the wall material would be slight and do not appear to substantially affect the result. Because of difficulties associated with extraction of wood blocks with water or alcohol, in this study density was determined on unextracted wood. However, in work presented later the effect of lignin and extractives on density is investigated.

TABLE 5.1 CHANGES IN THE STANDARD ERROR OF MEASUREMENT OF VARIABLES REQUIRED FOR GRAVIMETRIC DENSITY
DETERMINATION WHEN SAMPLE SIZE IS VARIED

Sample size based on oven dry weight	Standard error of measurement				
	Oven dry weight	Saturated weight In air	Saturated weight In water	Density by maximum moisture method	Density by water immersion method
14.604	0.009	0.008	0.001	0.0004	0.0003
13.566	0.009	0.008	0.000	0.0004	0.0003
11.632	0.010	0.009	0.001	0.0004	0.0003
10.331	0.008	0.008	0.001	0.0004	0.0003
9.832	0.006	0.008	0.002	0.0004	0.0003
8.438	0.005	0.007	0.001	0.0003	0.0002
7.908	0.006	0.005	0.002	0.0003	0.0008
4.231	0.006	0.005	0.002	0.0003	0.0008
1.003	0.003	0.006	0.002	0.0003	0.0011
0.090	0.001	0.009	0.003	0.0002	0.0009

5.3 RADIATION METHODS

The trend towards automation and the use of radio-isotopes or other forms of radiation has been apparent in wood density investigations during the last decade. Most of these new methods use a beam of fixed size and penetrating power on a sample of constant thickness thus obviating the need for volume determination.

These methods use expensive equipment and require control or measurement of moisture content and are not suited for direct determination of basic density. These methods, however, are particularly suited to describing continuous relative density variation patterns across a disc from pith to bark at a specified moisture content. By using several discs cut from various heights in a tree excellent indication of within tree variation is assured.

The three main radiation techniques are Beta-ray (Cameron *et al*, 1959), Gamma-ray (Jurasek and Jokel, 1963) and X-ray (Polge, 1963, 1965, 1966). Short descriptions of Beta-ray, X-ray and Gamma-ray radiation methods, as applied to determining wood density, have been given by Phillips (1965).

Eucalyptus deglupta has large vessels and is considerably more heterogeneous than the coniferous wood with which the radiation methods have been developed and tested. Irrespective of whether the radiation was directed tangentially or longitudinally with respect to the grain of the sample a relatively thick specimen would be needed to integrate effects of vessel elements.

Beta-rays have low penetrating power which varies with the isotope used. Beta-ray absorption technique using a Strontium 90 source having a half life of 28 years and high energy particles

would be suitable for measuring samples 0.5 to 0.8 cms in thickness (Cameron *et al*, 1959; Phillips, 1965; Harris, 1969). The sample is passed between the source of Beta-rays and a scintillation probe, the variations in particle count being converted electronically to a continuous record of wood density variation.

Gamma rays will also penetrate a range of thicknesses as gamma-ray sources covering a wide range of penetrating power are available (Phillips, 1965). This technique is especially suitable for thicker specimens (Loos, 1961). Specimens up to 6 cms in thickness have been used. The method could become more important in the future because of its portability and suitability for large thicknesses. However, it has not been widely used or sufficiently developed to use with confidence in this study.

The X-ray technique can also be used on fairly thick samples (Polge, 1963, 1964, 1965, 1966). In this technique, wood samples between 0.4 and 1.0 cms thickness are X-rayed and variations in optical density of the sample image on the film are translated into a continuous recording of relative wood density variation by a double-beam recording microdensitometer. With appropriate standards, these variations may be determined quantitatively.

Over the range of wood density from about 0.2 to 0.8 gms/cc, the relationship between wood density and optical density is almost linear (McKinnel, 1970). The theory has been outlined by Polge (1965).

Harris and Polge (1967) concluded that there was good agreement in density determination from X-ray and Beta-ray (Strontium-90) methods. However, examination of pairs of traces illustrating their paper showed X-rays to have superior resolving power. A Carbon 14 source used on

thin microtome sections improved the resolving power of the Beta-ray method (Phillips, 1968) but introduced problems with preparation of thin sections.

The use of thicker samples in the X-ray method was considered more advantageous for this study as small deviations in thickness became less significant and localised variations would be integrated.

With the large number of samples involved time taken in scanning the sample or radiograph became an important factor in deciding on a method. The X-ray densitometer scans at a rate of 10 cms/min as compared with only 0.1 cms/min for the Beta-ray apparatus. The use of groups of samples in preparation and X-ray exposure considerably reduces sample preparation time for the X-ray method. Further the X-ray plate once obtained, is a permanent record of the density variation throughout the sample. A positive photographic print, made from such a plate, serves as a readily visible record.

Reports of the use of X-ray-densitometric techniques on eucalypts are rare in the literature. The main study has been on *E. regnans* (Higgs, 1969). Having decided to use this method, the effects of technique modifications, sample orientation and instrumentation on the end result were studied.

(a) X-ray exposure

The distance between X-ray source and film was set at eight feet (2.5 m) to reduce blurring of the grain image towards the outer edges of the 10 x 8 inch (25 x 20 cm) film due to sample displacement from the beam axis. For samples at least one inch

(2.5 cms) in from the edge of the sheet, the maximum eccentricity from the beam axis is four inches (10 cm) and the corresponding blurring an acceptable 0.03 mm.

When X-rays are produced by the projection of electrons onto an anode, the spectrum of radiation produced has a peak emission wavelength which varies inversely with applied voltage. When wood is irradiated at a low voltage, the longer wavelength radiation in the spectrum is selectively absorbed, resulting in a non-linear relationship between wood density and optical density. An aluminium screen, 0.6 mm thick, placed in the path of radiation, near the source, improves linearity by attenuating longer wavelengths and reducing the width of the radiation spectrum.

Image resolution is greater at longer wavelengths of radiation. X-ray densitometry involves a compromise between image sharpness and linearity of the wood density: optical density calibration curve. In addition to the type of emission spectrum produced, the voltage applied affects the exposure time for a given film rating.

Consequently to determine wood density quantitatively, there are four main requirements:

- i. A voltage which gives the best compromise between image resolution and optical density/wood density linearity.
- ii. An exposure time which correctly exposes a particular film type.
- iii. A set of artificial density standards with which to compare wood density.

- iv. A calibration curve to relate optical density of the X-ray plate to wood density.

The calibration of the X-ray apparatus used in this study has been described in detail elsewhere (McKinnell, 1970; Rudman *et al*, 1969).

- (b) Size of slit used in optical scanning and sample orientation

Optical scanning was carried out on a Joyce-Loebel Mark III C.S. dual beam recording micro-densitometer (Figure 5.2) (Plate 5.1).

The degree to which the effects of the large vessels are integrated would be affected by the size of the beam passing through the X-ray plate. The size of this beam is controlled by the sub-stage condensor lens magnification, the diaphragm aperture diameter and the slit width (Figures 5.2 and 5.4).

The sample may be arranged on the X-ray plate with longitudinal elements (fibres, vertical parenchyma, vessels) parallel to the radiation or on its side so that radiation passes tangentially or at right angles to the longitudinal elements and the rays (Figure 5.3).

The combined effects of beam size and sample orientation were investigated for several test samples of *E. deglupta*. Density determined by the maximum moisture content method was used as a standard.

Figure 5.5 shows two radiographs and two series of densitometer traces illustrating the effects of instrument settings and sample orientation on the type of curve produced. Twelve samples were investigated and results are summarised in Table 5.2.

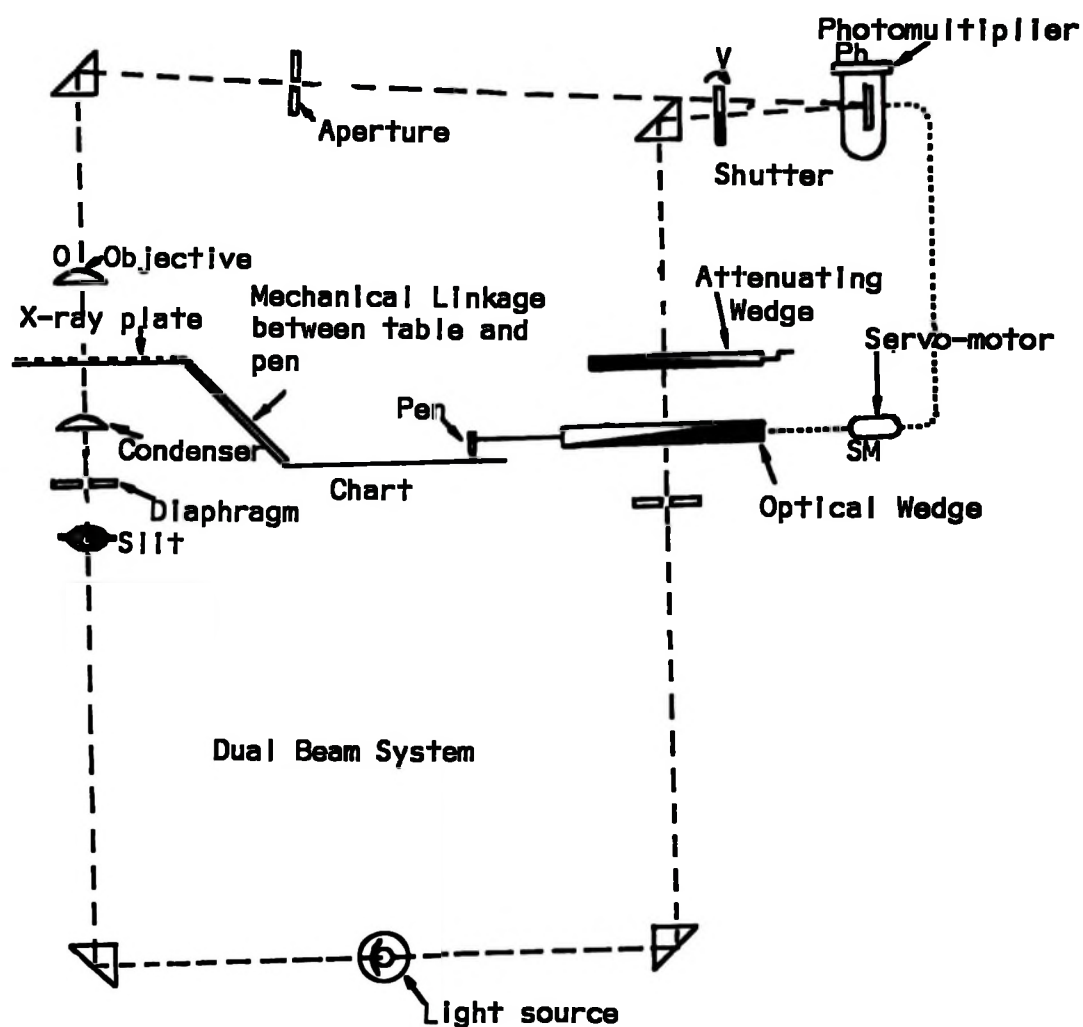


FIGURE 5.2 Diagram of light paths in densitometer.

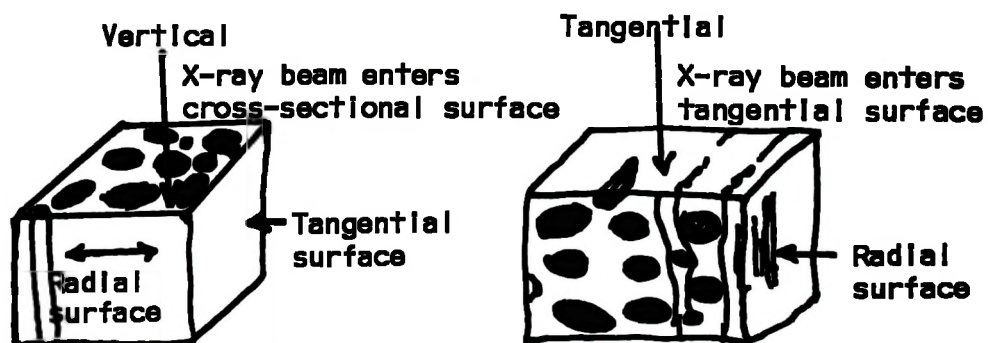


FIGURE 5.3 Orientation of wood block for irradiation by x-rays.

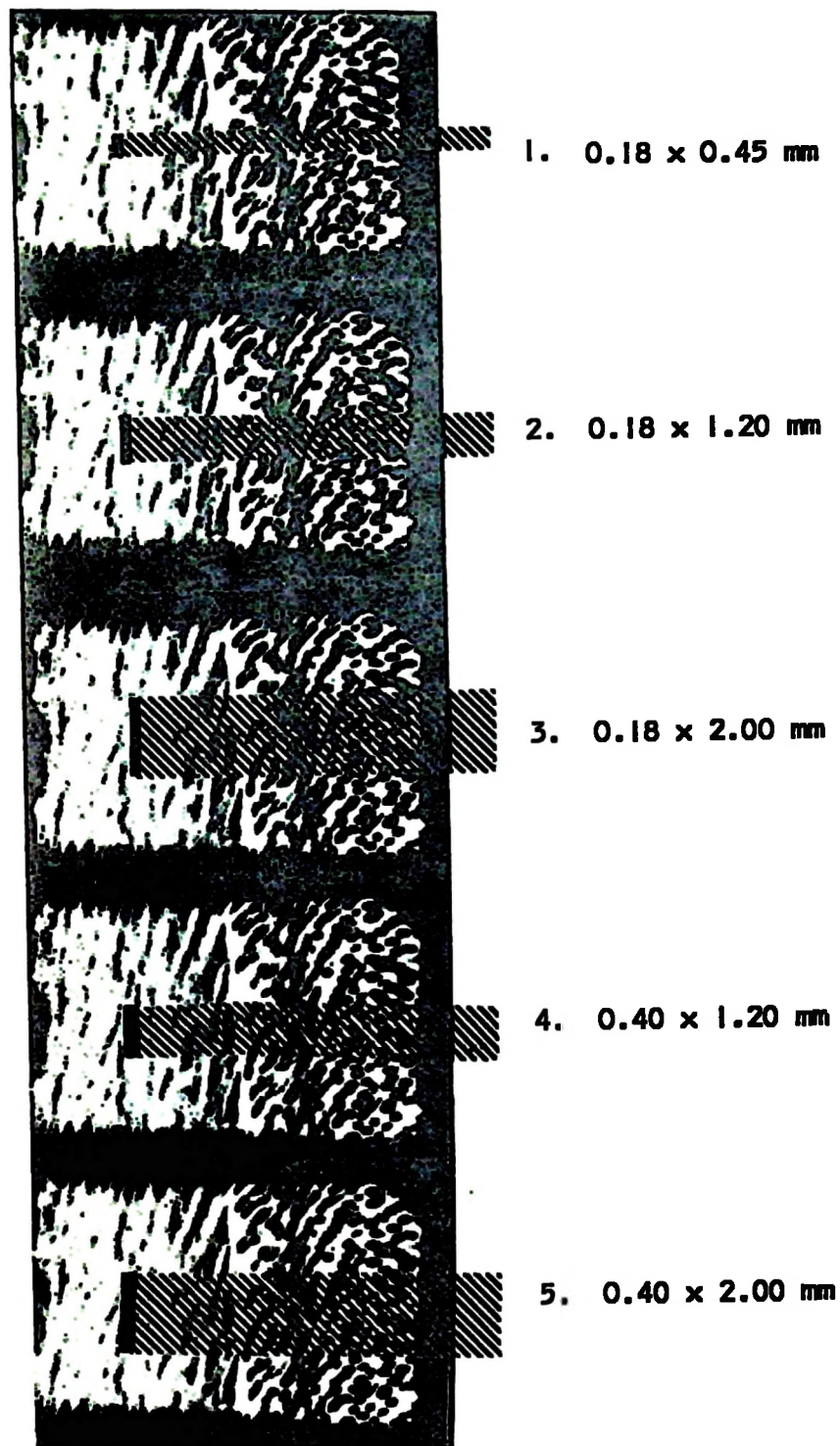


FIGURE 5.4 Five slit sizes superimposed on X-ray images of *E. deglupta* wood magnified to the same degree. The larger slits are more effective in integrating vessel effects.

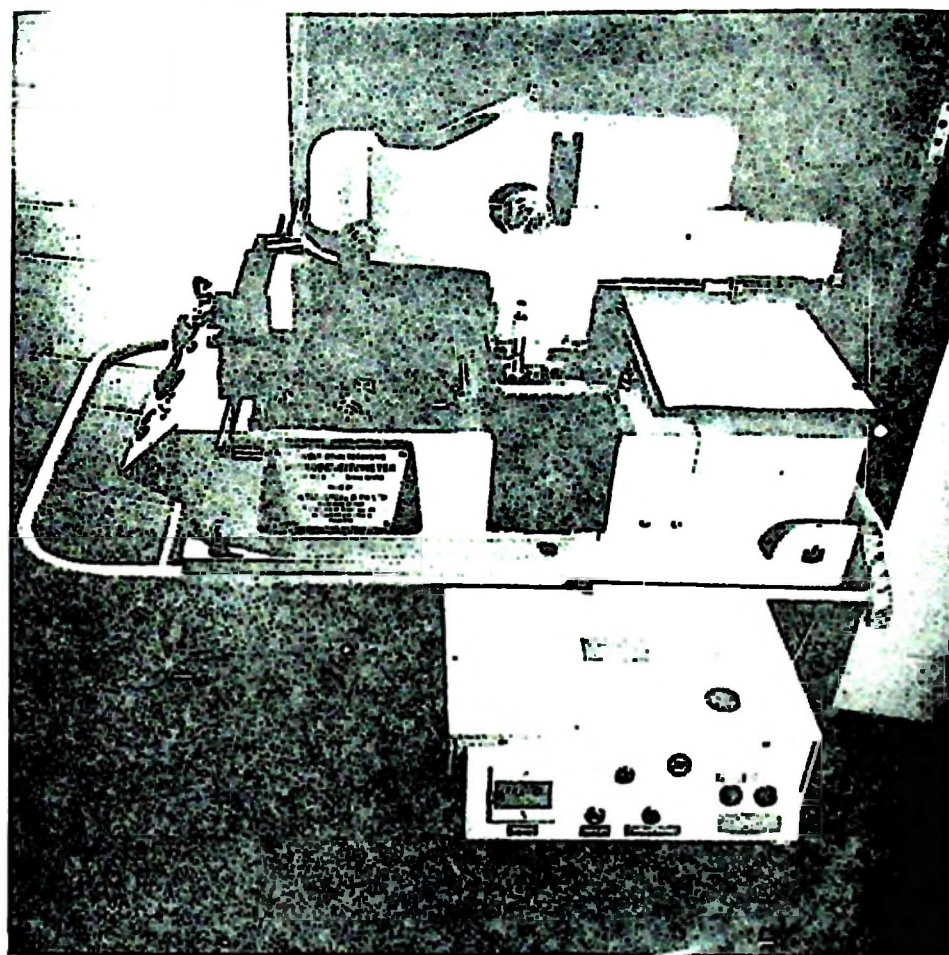


PLATE 5.1 Joyce Loebel double-beam recording microdensitometer.

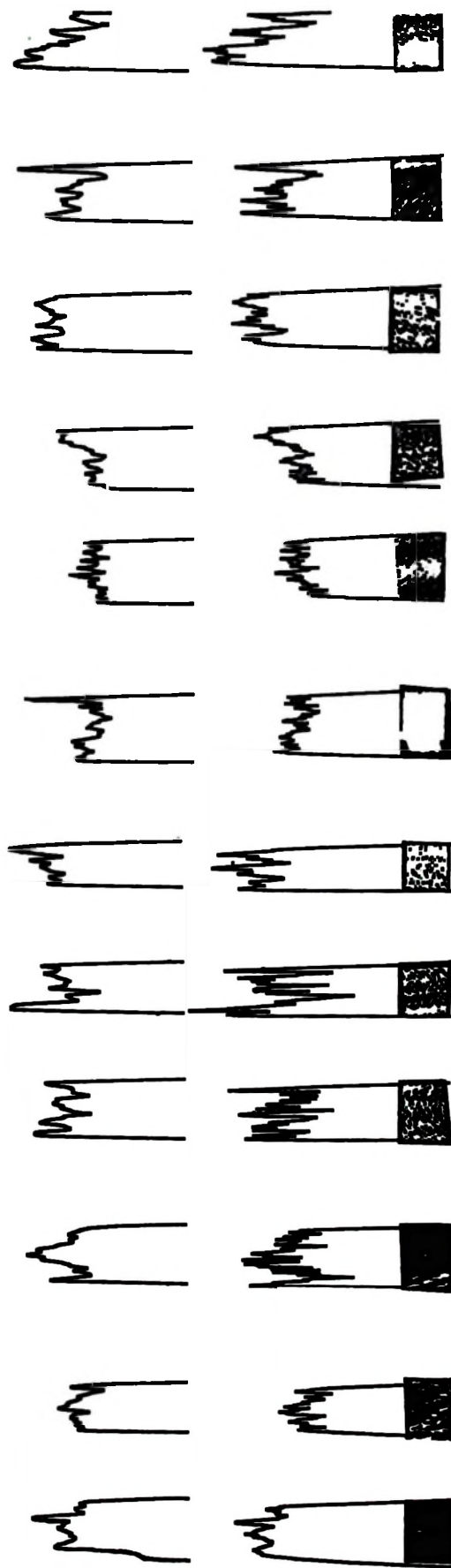


FIGURE 3.5A The series of denitrometer tracings on twelve used blocks 2-traced in the vertical direction. 2-ray images of the blocks are compared with the smallest slit area (number 1 in Figure 3.43) in the lower row and with the largest slit area (number 2 in Figure 3.45) in the upper row.

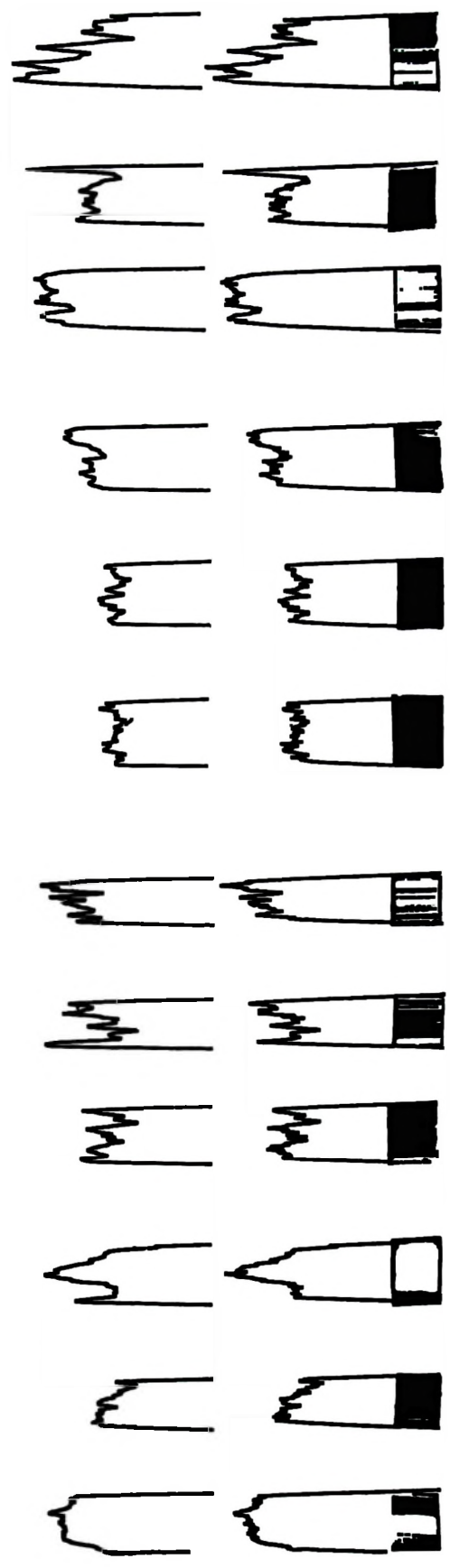


FIGURE 3.20 The series of denitrifier incubations on twelve sand blocks scraped in the tangential direction. X-ray images of the blocks are compared with the smallest silt size (number 1) in Figures 3.43 to the lower row and with the largest silt size (number 5) in Figures 3.47 to the upper row.

TABLE 5.2 DENSITY OF SAMPLE BLOCKS X-RAYED LONGITUDINALLY AND TANGENTIALLY COMPARED WITH DENSITY BY MAXIMUM MOISTURE CONTENT METHOD

Sample Number	D_{MM}	X-ray - Longitudinal Orientation					X-ray - Tangential Orientation				
		1†	2	3	4	5	1	2	3	4	5
1	0.344	0.360	0.363	0.378	0.380	0.381	0.338	0.340	0.345	0.346	0.345
2	0.332	0.358	0.368	0.375	0.374	0.371	0.332	0.339	0.345	0.345	0.345
3	0.378	0.371	0.390	0.378	0.374	0.382	0.372	0.394	0.406	0.405	0.400
4	0.436	0.465	0.480	0.495	0.495	0.490	0.504	0.500	0.506	0.490	0.505
5	0.388	0.440	0.425	0.439	0.534	0.439	0.372	0.400	0.404	0.400	0.400
6	0.442	0.430	0.438	0.470	0.466	0.480	0.405	0.425	0.452	0.425	0.445
7	0.442	0.550	0.560	0.572	0.559	0.565	0.517	0.520	0.519	0.512	0.520
8	0.442	0.450	0.440	0.453	0.460	0.450	0.402	0.399	0.415	0.405	0.410
9	0.427	0.498	0.498	0.505	0.524	0.515	0.473	0.480	0.497	0.484	0.482
10	0.432	0.480	0.495	0.530	0.506	0.500	0.391	0.400	0.405	0.408	0.418
11	0.451	0.480	0.480	0.515	0.533	0.490	0.405	0.405	0.410	0.405	0.415
12	0.518	0.590	0.585	0.582	0.592	0.594	0.483	0.480	0.510	0.495	0.500
Mean	0.419	0.456	0.460	0.474	0.483	0.471	0.416	0.424	0.435	0.427	0.432

The mean values are not significantly different at the five per cent level.

†Slit sizes. Numbers refer to slit settings given in Figure 5.4

The magnitude of mean values and matrix of correlation coefficients and their significance are given in Table 5.3.

The correlation coefficients for results obtained when the sample is orientated longitudinally show more consistent agreement with the gravimetric method than do those for samples X-rayed tangentially. Also longitudinal orientation consistently provided density values about ten per cent greater than those derived from tangentially orientated specimens.

The change in area of the scanning beam, within the limits tested, did not appear to affect the density value obtained.

The density value obtained in X-ray densitometry is of the form (weight at specified moisture content/volume at same specified moisture content). This moisture content is about eight per cent by weight as samples were equilibrated over a saturated solution of sodium dichromate in a sealed vessel at room temperature.

The density value obtained gravimetrically uses an oven-dry (moisture free) weight and a saturated volume. In comparing the radiation and gravimetric methods one must, therefore, take into consideration that the X-ray volume is much less (shrinkage takes place from a moisture content below saturation to eight per cent moisture content) and weight slightly more (due to presence of eight per cent moisture by weight) thus we should expect inflated density values.

It was decided to use the largest slit area tested. The shape chosen being a rectangle much wider in the direction at right angles to the direction of travel so that radial variation would not be masked. Longitudinal orientation was accepted because of its apparently higher correlation with gravimetrically determined density.

TABLE 5.3 MATRIX OF CORRELATION COEFFICIENTS BETWEEN DENSITY OBTAINED BY MAXIMUM MOISTURE CONTENT METHOD

AND X-RAY METHODS

Longitudinal Orientation						Tangential Orientation					
D_{AM}	1†	2	3	4	5	1	2	3	4	5	
D_{AM}	1.000	0.060	0.065	0.064	0.097	0.055	0.134	0.143	0.120	0.128	0.115
1	0.890***	1.000	0.006	0.017	0.034	0.010	0.090	0.099	0.094	0.085	0.085
2	0.880***	0.989***	1.000	0.011	0.053	0.008	0.076	0.084	0.082	0.071	0.069
3	0.882***	0.970***	0.980***	1.000	0.046	0.010	0.097	0.107	0.107	0.100	0.089
4	0.820***	0.939***	0.903***	0.918***	1.000	0.046	0.135	0.131	0.133	0.128	0.124
5	0.900***	0.982***	0.986***	0.983***	0.916***	1.000	0.078	0.084	0.077	0.073	0.066
1	0.732**	0.829***	0.859***	0.814***	0.730**	0.854***	1.000	0.008	0.015	0.011	0.010
2	0.711**	0.811***	0.842***	0.795***	0.739**	0.842***	0.987***	1.000	0.007	0.004	0.004
3	0.765**	0.820***	0.846***	0.793***	0.734**	0.857***	0.974***	0.988***	1.000	0.004	0.004
4	0.747**	0.840***	0.869***	0.809***	0.747**	0.864***	0.981***	0.993***	0.993***	1.000	0.004
5	0.777**	0.840***	0.873***	0.832***	0.756**	0.879***	0.982***	0.992***	0.994***	0.993***	1.000

†Silt sizes. Numbers refer to silt settings given in Figure 5.4

*** $r > 0.780$ significant at 0.1 per cent level** $r > 0.661$ significant at 1 per cent level* $r > 0.532$ significant at 5 per cent level

Lower left triangular part of table gives correlation coefficients and their significance. Upper right triangle standard error of correlation coefficients.

All the density methods to be used in this study have been described together here for convenience. The maximum moisture method was used for small wood blocks about 1 cc in volume (Chapter 6), the water immersion method was used on pith to bark cores removed from standing trees (Chapter 12) and the X-ray method for obtaining continuous traces of pith to bark variation in a study of within tree wood density (Chapter 7).

CHAPTER 6

THE ASSOCIATION BETWEEN WOOD DENSITY AND OTHER MEASURED WOOD PARAMETERS

6.1 INTRODUCTION

In Chapter 4, the importance of fibre characters and, in particular, relative amount of fibre wall material present, was shown. Wood density, as defined in Chapter 5, is a measure of the amount of wall material present in a given volume of wood and so should be related positively to the components featuring amount of wall material and negatively to components featuring voids. It could be expected that this relationship would be excellent but for complicating factors such as the presence of extraneous materials and the chemical composition of the cell walls.

The relationship of wood density with other wood parameters has been examined by taking the same experimental material as was used in Chapter 4 and determining the density of each sample by the maximum moisture content method, previously described. How well the density parameter characterized a wood sample was judged by attempting to fit it to the same four-component model of the total wood variation developed in Chapter 4.

6.2 RESULTS AND ANALYSIS

The density data was subjected to the programme SCREEN to test for normality. Dispersion statistics for tree number one are given

In Table 6.1 as an example of out-put. There is no evidence to reject the null hypothesis that the density data is normally distributed. Product-moment correlations were computed, using programme CORRE, to test the association between density and the other previously measured parameters (Table 6.2).

The data set, including density, was then subjected to principal components and factor analysis, using the programme FACTO.

6.3 FITTING THE DENSITY PARAMETER TO THE FOUR-COMPONENT DESCRIPTION OF WOOD VARIABILITY

A principal component analysis of all data including density indicated that density could be absorbed into the four-component representation without changing its structure. Table 6.3 shows a comparison of eigen values, and percentage variance removed by the four-component system when density is omitted or included. There is very little difference between members of the paired values in the table indicating that both representations are similar. A factor analysis produces correlations between the components and wood density (Table 6.4). A rotated factor analysis is again of some benefit in interpretation (Table 6.5).

On examination of Tables 6.4 and 6.5, it seems very reasonable to identify density strongly with components 1 and 3, which, in turn, represent some 70 per cent of the total variability in the wood of *E. deglupta*. A weak association with the second component is evident. Component 2 represents some 19 per cent of the variability. There is almost no association of density with the fourth component.

TABLE 6.1 DISPERSION STATISTICS FOR WOOD DENSITY

Statistic	Measurement unit	Value	Standard Error	95 Per cent Confidence Limits	
				Lower	Upper
Mean	gms	0.499	0.011	0.477	0.521
Median	gms/cc	0.500	0.014	0.473	0.527
Variance	gms/cc	0.006			
Standard Deviation	gms/cc	0.080			
Coefficient of Variation	per cent	16.02	1.58	12.85	19.19
Skewness		0.77	0.32	0.14	1.41
Kurtosis		1.37	0.64	0.12	2.62
Kolmogorov-Smirnov Statistic		0.099*			

*Critical value of the Kolmogorov-Smirnov Statistic = 0.181 at the five per cent probability level.

TABLE 6.2 CORRELATION COEFFICIENTS BETWEEN WOOD DENSITY AND
OTHER MEASURED PARAMETERS

		r	
		Correlation with density	Standard error of the
		(x_{25} (DENS))	correlation coefficient
x_1	(FL)	+0.41 ***	0.04
x_2	(2W)	-0.50 ***	0.03
x_3	(L)	+0.66 ***	0.03
x_4	(D)	+0.48 ***	0.04
x_5	(RV)	-0.12 **	0.05
x_6	(FV)	+0.11 *	0.05
x_7	(VV)	+0.00	0.05
x_8	(VNO)	-0.42 ***	0.04
x_9	(VS)	+0.25 ***	0.04
x_{10}	(FL/D)	+0.19 ***	0.04
x_{11}	(2W/L)	+0.72 ***	0.02
x_{12}	(2W/D)	+0.75 ***	0.02
x_{13}	(L/D)	-0.75 ***	0.02
x_{14}	(FIBS)	-0.50 ***	0.03
x_{15}	(WA)	+0.62 ***	0.03
x_{16}	(FA)	+0.53 ***	0.03
x_{17}	(LA)	-0.45 ***	0.04
x_{18}	(WA/FA)	+0.75 ***	0.02
x_{19}	(LA/FA)	-0.74 ***	0.02
x_{20}	(LA/WA)	-0.75 ***	0.02
x_{21}	(FIBS/A)	-0.52 ***	0.03
x_{22}	(LIG)	+0.17 ***	0.04
x_{23}	(EXT)	+0.31 ***	0.04
x_{24}	(HOLO)	-0.18 ***	0.04
x_{25}	(DENS)	1.00	0.00

* $r > 0.09$ significant at five per cent level

** $r > 0.12$ significant at one per cent level

*** $r > 0.15$ significant at 0.1 per cent level

**TABLE 6.3 COMPARISON OF TWO FOUR-COMPONENT REPRESENTATIONS OF
WOOD VARIABILITY WHEN DENSITY IS EITHER INCLUDED (A)
OR OMITTED (B)**

		COMPONENT			
		1	2	3	4
Eigen values	A	15.54	5.24	3.12	1.11
	B	14.05	4.52	2.85	1.01
Eigen value as a percentage of total	A	57.5	19.4	11.6	4.1
	B	58.5	18.8	11.9	4.2
Cumulative percentage of eigen values (variance removed)	A	57.5	77.0	88.5	92.6
	B	58.5	77.4	89.3	93.5

TABLE 6.4 CORRELATIONS BETWEEN DENSITY AND THE FOUR COMPONENTS OF WOOD VARIATION DETERMINED BY FACTOR ANALYSIS

	F_1	F_2	F_3	F_4	Density
F_1	1.000				
F_2	0.0	1.000			
F_3	0.0	0.0	1.000		
F_4	0.0	0.0	0.0	1.000	
Density	<u>+0.609</u>	<u>-0.472</u>	<u>+0.354</u>	<u>+0.055</u>	1.000

The four factors F_{1-4} refer to the four components ξ_{1-4} in Table 4.5. $F_i = \xi_{i2} \cdot \lambda^{-0.5}$

TABLE 6.5 CORRELATIONS BETWEEN DENSITY AND THE FOUR COMPONENTS OF WOOD VARIATION DETERMINED BY FACTOR ANALYSIS AND VARIMAX ROTATION

	F_1	F_2	F_3	F_4	Density
F_1	1.000				
F_2	0.0	1.000			
F_3	0.0	0.0	1.000		
F_4	0.0	0.0	0.0	1.000	
Density	<u>+0.669</u>	<u>-0.171</u>	<u>+0.481</u>	<u>+0.114</u>	1.000

6.4 DISCUSSION

The interpretation of the correlations between density and the other measured parameters again requires caution. Most of the significant correlations could be caused by positional effects, one example is fibre lumen diameter. Fibre lumen diameter would be expected to be negatively correlated with density because, if lumen diameter was increased, density should decrease because of increased size of voids. Instead, the correlation coefficient is positive, possibly because both fibre lumen diameter and density increase together from the pith outwards. Also, fibres with larger lumens tend to have thicker walls so more solid material is present to raise the density. The factor analysis has indicated density is negatively correlated with the factor containing fibre lumen diameter when the effects of other variables are removed.

Considering that density is well correlated with the first and third components and slightly correlated with the second component, it is able to describe more than 70 per cent of the variability of *E. deglupta* wood.

The low correlation of density with the second component means that density varies independently of tissue proportions, vessel size, extractives and the chemical constituents of the cell walls. There would be no advantage to be gained by extracting *E. deglupta* wood prior to density determinations.

It is difficult to determine if the present study could be used to predict the importance of density for describing the wood of other species or genera of hardwoods as *E. deglupta* is a diffuse porous hardwood without distinct growth rings grown in a fairly uniform climate. Few similar studies have been made.

Most authors found density to be associated with fibre cross-sectional parameters. A strong relationship between wood specific gravity and fibre diameter was reported by Ferreirinha (1953) in a study of 28 different tropical hardwood genera. Pechmann (1958) found fibre wall thickness was the major factor controlling wood density variation in ash. In *Shorea* species wood density outwards from the pith was observed by Myint Aung (1960, 1962) to be associated with cross fibre dimensions, particularly fibre diameter. Between stand, between trees and within tree variations of wood specific gravity in *Terminalia superba* were observed by Mottet (1963) to be associated with the fibre flexibility ratio (the ratio fibre lumen diameter:fibre diameter). Fibre cross-sectional dimensions were found by Chudnoff and Tischler (1963) to account for almost all of the total variation in density of extractive free wood in *Eucalyptus camaldulensis*. Scaramuzzi and Ferrari (1963) found a close linear relationship between fibre cross-sectional dimensions (fibre wall thickness and fibre diameter that order) and wood specific gravity at between tree, between stand and between species levels in *Populus* material; the combined factors accounting for 90 per cent of the total variation. Mottet (1965) has shown an excellent relationship between density and flexibility coefficient for tropical woods.

In regard to volume proportion of tissues, a small number of studies has shown conflicting results. Schulz (1957) found wood density variations in beech were associated with variation in fibre volume proportion while Myint Aung (1960, 1962) and Scaramuzzi and Ferrari (1963) attached no significance to volume proportion of tissues.

The above studies are insufficient to determine if any pattern is emerging. Detailed studies of wood variation will be required for each species examined until such time as a general or group pattern is found. Perhaps separate investigations will always be required for every species and geographic locality considered.

One important aspect, not so far considered in detail is the effect of position within the tree on wood parameters and sample representativeness. This is considered in the next Chapter.

CHAPTER 7

SYSTEMATIC VARIATION OF MEASURED WOOD PROPERTIES WITHIN INDIVIDUAL STEMS AND ITS EFFECT ON SAMPLE REPRESENTATIVENESS

7.1 INTRODUCTION

Systematic variation in wood characteristics within trees complicates comparisons between trees. These variation patterns are caused by genetic and environmental effects. Some precautions to be observed in sampling procedures to minimize the effect of systematic variation in wood characteristics within the tree have been set out by Nicholls and Dadswell (1962). They observed that, in *Pinus radiata* D. Don, it was not proper to compare tracheid lengths between even aged trees which showed differences in early height growth if the trees were sampled at a fixed distance above ground. Richardson (1961) has suggested that samples should be located with reference to the number of internodes from the apex. Chalk (1961) has indicated that, ideally, sampling should be carried out at a level which is proportional to the height of the tree. In addition, consideration must be given to conflicting requirements such as the need to avoid disturbances near the tree base (Nicholls and Dadswell, 1962) and the convenience of being able to sample from ground level.

For successful evaluation of wood properties, the establishment of inherent within tree variation patterns in *Eucalyptus deglupta* is a pre-requisite for successful sampling and for assessment and comparison of different genotypes.

Using the same sample material as used in Chapters 4 and 6, an attempt was made to relate the measured parameters to their origin in the stem with respect to height above ground and radial distance from the pith.

7.2 CORRELATION ANALYSIS

A product-moment-correlation analysis was computed (programme CORRE) to determine the association between all measured parameters (including density) and position in the stem (Table 7.1). For distance from the pith, there are 24 parameters correlated at the 0.1 per cent level, and one at the 5 per cent level of significance out of a total of 26. For height above ground, there are 23 parameters with correlation coefficients significant at the 0.1 per cent level and two at the one per cent level, out of a total of 26. Because of the large numbers of degrees of freedom in the analysis the levels of significance have little value but correlations of 0.80 and above are important. The fibre characters lumen diameter and fibre diameter and those variables derived from them are strongly associated with distance from the pith. These results mean that many of the significant correlations between pairs of variables in Table 4.3 and 6.2 were due to the common effect of within-tree position acting on both (models 3-5 in Table 4.4). Principal component and factor analyses were again used to determine independent effects of the two position variables on the remainder.

TABLE 7.1 PRODUCT-MOMENT CORRELATION COEFFICIENTS FOR ALL
COMBINATIONS OF MEASURED WOOD PARAMETERS AND WITHIN
TREE POSITION

Variable	Distance from Pith		Height above Ground	
	r	S.E.	r	S.E.
x_1 (FL)	+0.73***	0.02	-0.17***	0.04
x_2 (2W)	-0.15***	0.04	-0.18***	0.04
x_3 (L)	+0.95***	0.00	-0.24***	0.04
x_4 (D)	+0.92***	0.01	-0.33***	0.04
x_5 (RV)	+0.31***	0.04	-0.88***	0.01
x_6 (FV)	+0.55***	0.03	-0.60***	0.03
x_7 (VV)	-0.48***	0.04	+0.83***	0.01
x_8 (VNO)	-0.74***	0.02	+0.20***	0.04
x_9 (VS)	-0.02	0.05	+0.66***	0.03
x_{10} (FL/D)	+0.32***	0.04	-0.02	0.05
x_{11} (2W/L)	+0.90***	0.01	-0.20***	0.04
x_{12} (2W/D)	+0.91***	0.01	-0.17***	0.04
x_{13} (L/D)	-0.91***	0.01	+0.18***	0.04
x_{14} (FIBS)	-0.89***	0.01	+0.28***	0.04
x_{15} (WA)	+0.97***	0.00	-0.28***	0.04
x_{16} (FA)	+0.97***	0.00	-0.31***	0.04
x_{17} (LA)	-0.10*	0.05	-0.13**	0.05
x_{18} (WA/FA)	+0.90***	0.01	-0.16***	0.04
x_{19} (LA/FA)	-0.88***	0.01	+0.12**	0.05
x_{20} (LA/WA)	-0.90***	0.01	+0.16***	0.04
x_{21} (FIBS/A)	-0.94***	0.01	+0.28***	0.04
x_{22} (LIG)	+0.63***	0.03	-0.86***	0.01
x_{23} (EXT)	+0.68***	0.02	-0.77***	0.02
x_{24} (HOL)	-0.63***	0.03	+0.83***	0.01
x_{25} (DENS)	+0.73***	0.03	+0.17***	0.04
x_{26} (DPTH)	1.00	0.00	-0.32***	0.04
x_{27} (HT)	-0.32***	0.04	1.00	0.00

r = correlation coefficients

S.E. = standard error of correlation coefficients

* r > 0.09 significant at five per cent level

** r > 0.12 significant at one per cent level

*** r > 0.15 significant at 0.1 per cent level

7.3 PRINCIPAL COMPONENT AND FACTOR ANALYSES

The height and radial distance from pith parameters can be incorporated into the same four-component model already developed. An inspection of the correlations of the two new variables with the components as determined from normal and rotated factor matrices (Tables 7.2 and 7.3) show two important sets of correlations (indicated in bold type and underlining). Radial distance from the pith is strongly associated with the first component of variation ($r = 0.896$, Table 7.3). Height is associated with the first and fourth components, but more strongly to the latter, the less important one ($r = 0.759$, Table 7.3). For the fibre variables associated with the first component, position within the tree, with respect to both distance from the pith and height above ground, is very important. As density is strongly related to the first component, it will also be affected by position.

Important parameters in the second component, such as extractives, chemical composition of cell walls and proportion of tissue types are shown to be independent of systematic positional effects. The high correlations for these in Table 7.1 were probably determined by unknown effects in addition to position as postulated in Table 4.4. This example shows the value of principal component analysis over correlation analysis.

Fibre lumen diameter and lumen area in the second component are also independent of position effects. The high correlation of fibre lumen diameter with distance from the pith shown in Table 7.1 was probably due to its high correlation with some other variable such as fibre diameter.

Height above ground is strongly associated with the fourth component representing fibre length and fibre length to diameter

TABLE 7.2 CORRELATIONS BETWEEN THE FOUR-COMPONENT REPRESENTATION OF WOOD VARIABILITY (DETERMINED BY NORMAL FACTOR ANALYSIS) AND RADIAL DISTANCE FROM PITH AND HEIGHT ABOVE GROUND

	F_1	F_2	F_3	F_4	Radial Distance	Height
F_1	1.000					
F_2	0.0	1.000				
F_3	0.0	0.0	1.000			
F_4	0.0	0.0	0.0	1.000		
Radial distance	<u>0.895</u>	0.123	0.280	-0.242	1.000	
Height	<u>0.637</u>	0.544	0.357	0.331	-0.316	1.000

The four factors F_{1-4} correspond to the four components ξ_{1-4} in Table 4.5. $F_i = \xi_i \lambda^{-0.5}$

TABLE 7.3 CORRELATIONS BETWEEN THE FOUR-COMPONENT REPRESENTATION OF WOOD VARIABILITY (DETERMINED BY ROTATED FACTOR ANALYSIS) AND RADIAL DISTANCE FROM PITH AND HEIGHT ABOVE GROUND

	F_1	F_2	F_3	F_4	Radial Distance	Height
F_1	1.000					
F_2	0.0	1.000				
F_3	0.0	0.0	1.000			
F_4	0.0	0.0	0.0	1.000		
Radial Distance	<u>0.896</u>	-0.278	0.236	0.133	1.000	
Height	<u>0.595</u>	0.0	0.098	<u>0.759</u>	-0.316	1.000

ratio but this is of little importance because the fourth component only represents some four per cent of wood variation.

Before proceeding to a discussion of the implications of within tree variability for sampling and sample representativeness, variation patterns of some of the measured parameters will be illustrated and discussed.

7.4 VARIATION PATTERNS OF SOME MEASURED WOOD PARAMETERS

(a) Fibre length

Diagrams, depicting the variation in fibre length in a plane extending from pith to bark in the north direction and from ground level to 70 per cent of total tree height, are given for two of the nine trees of *E. deglupta* (Figure 7.1). The vertical scale has been compressed some 100 times while the horizontal scale has been compressed only four times.

In the smaller trees, there is a fairly regular increase of fibre length from pith to bark. However, in the outer part of the stems fibre length becomes variable with respect to height above ground. Fibre length increases from ground level to a maximum between about 10 and 50 per cent of final tree height, then decreases again. In the larger diameter trees, fibre length has begun to fluctuate in the outer parts of the trunk but still rises to a maximum some distance above ground level, then decreases with height.

The component analysis supports this pattern of observed variation by showing an association between the fourth component, containing fibre length, and height.

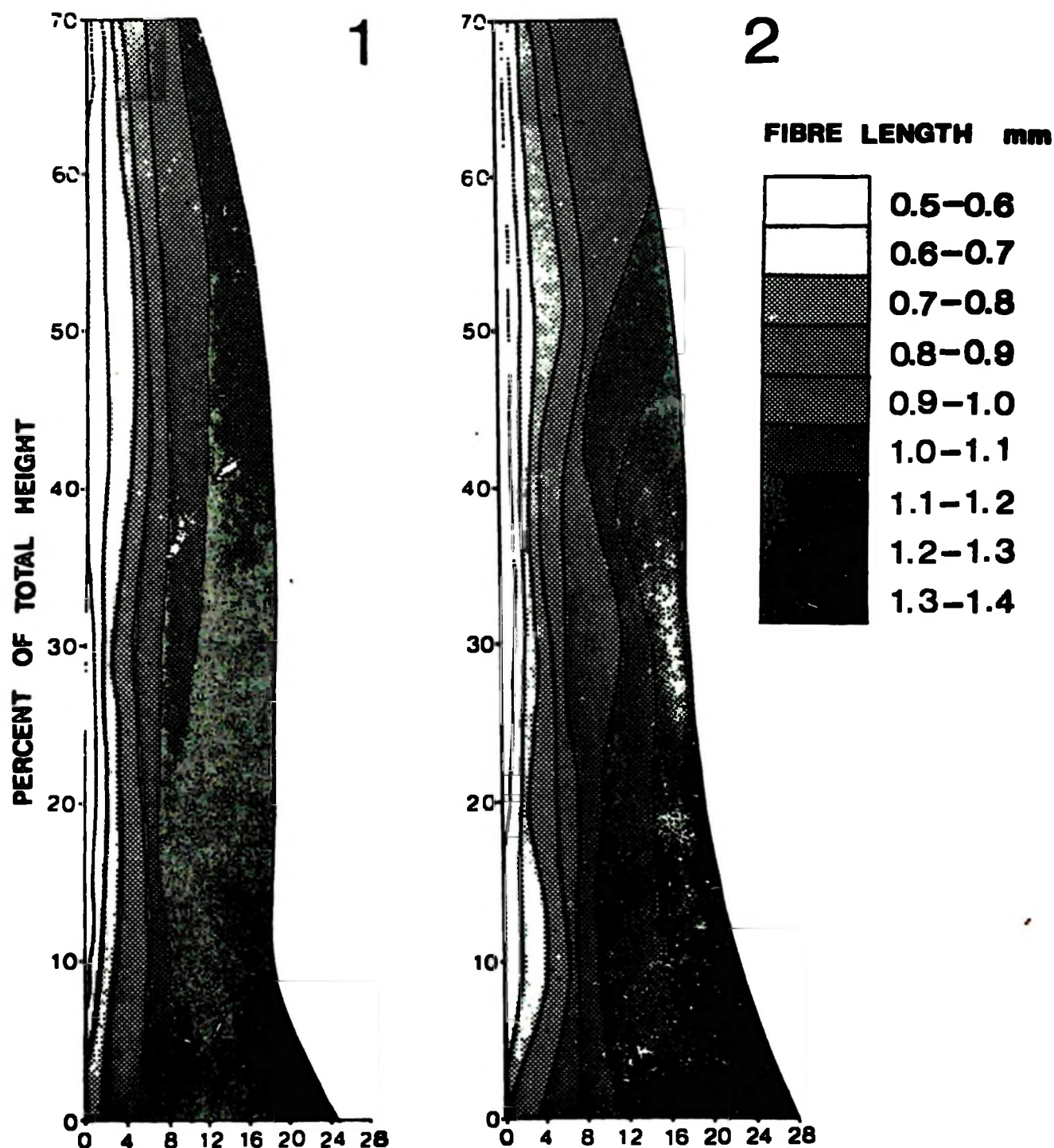


FIGURE 7.1 Fibre length variation in two trees of *E. deglupta*. In this and following figures showing variation in wood properties, the portion of the trunk represented is a plane orientated in the northerly direction extending from pith to bark and from ground level to 70 per cent of total tree height. Tension wood was avoided during the study, so is not primarily responsible for the patterns obtained.

These results are consistent with the early rules for systematic variation in cell length in trees formulated by Sanio (1872; see Bailey and Shephard, 1915) after he made a detailed examination of *Pinus sylvestris* L. Two of his five rules are relevant here. They are:

- I. 'In the stem and branches, the tracheids* everywhere increase in size from within outwards, throughout a number of annual rings until they have attained a definite size which then remains constant for the remaining rings.
- II. The constant final size changes in such a manner that it instantly increases from below upwards, reaches a maximum at a definite height, then diminishes towards the summit'.

Since 1872, Sanio's first rule has been supported by many studies although observed variations have been less regular than Sanio suggested and variable within and between species, e.g., *Populus* species (Scaramuzzi, 1955), *Eucalyptus regnans* (Bisset and Dadswell, 1949; Higgs, 1969), *Liriodendron tulipifera* (Thorbjornson, 1961), *E. gomphocephala* (Stern-Cohen and Fahn, 1964), *E. grandis* (Ranatunga, 1964; Bamber and Humphreys, 1963), *Populus tremuloides* (Brown and Valentine, 1962), *Tectona grandis* (Kedharnath *et al*, 1963), *E. camaldulensis* (Chudnoff and Tischler, 1963), *Quercus* species (Elchhorn, 1895), and *Fraxinus* (Desch, 1932).

*Tracheids and fibres are used synonymously in this thesis as terms for the dominant, axially orientated wood elements.

The maximum, and sometimes constant, value of fibre length is reached early or late in life depending on the species in question. If uniformity of wood is a requirement, an early rise to a fairly constant maximum is a desirable feature. It would appear that fibre length has begun to oscillate around a maximum value in *E. deglupta* trees 5, 7, 8 and 9.

- Maximum fibre length has been observed at between 20 and 40 per cent of final height of the stem in *Quercus falcata* (Hamilton, 1961), *Liriodendron tulipifera* (Thobjornsen, 1961), *Fraxinus pennsylvanica* (Saucier and Hamilton, 1967), *E. grandis* (Ranatunga, 1964; Bamber, 1964), *E. gomphocephala* (Stern-Cohen and Fahn, 1964) and *E. regnans* (Bisset *et al*, 1949; Higgs, 1969).

However, other patterns of variation with height have also been reported. A continuous decrease with increasing height has been observed in *Populus japono-gigas* (Inokuma *et al*, 1956), *Populus robusta* (Liese and Ammer, 1958), *Liriodendron tulipifera* (Taylor, 1968), several hardwoods (Hartig, 1894), *E. regnans* (Ranatunga, 1964), *Fraxinus* (Desch, 1932). Hejnowicz and Hejnowicz (1958) reported that, in a single tree of *Populus tremula*, fibre length at a constant cell number from the pith remained fairly constant with height. Anderson (1951) found in some species tracheids were longer in the upper parts of the stem at points equidistant from the pith.

(b) Fibre-cross-sectional dimensions

The variation patterns for fibre double-wall thickness, fibre lumen diameter and fibre diameter in *E. deglupta* (Figures 7.2, 7.3 and 7.4) are more complicated than those for fibre length.

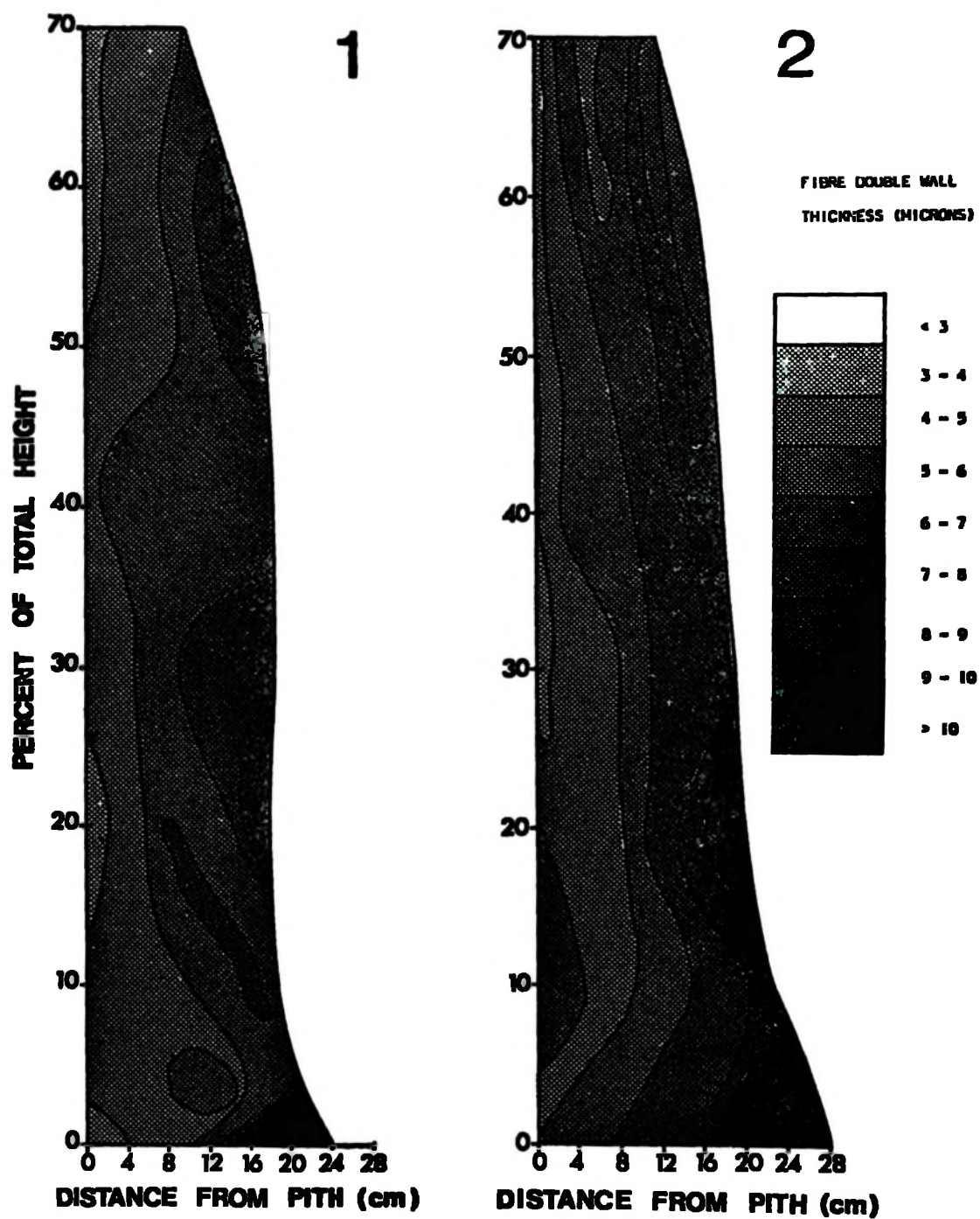


FIGURE 7.2 Variation in fibre double wall thickness in two trees of *E. deglupta*.

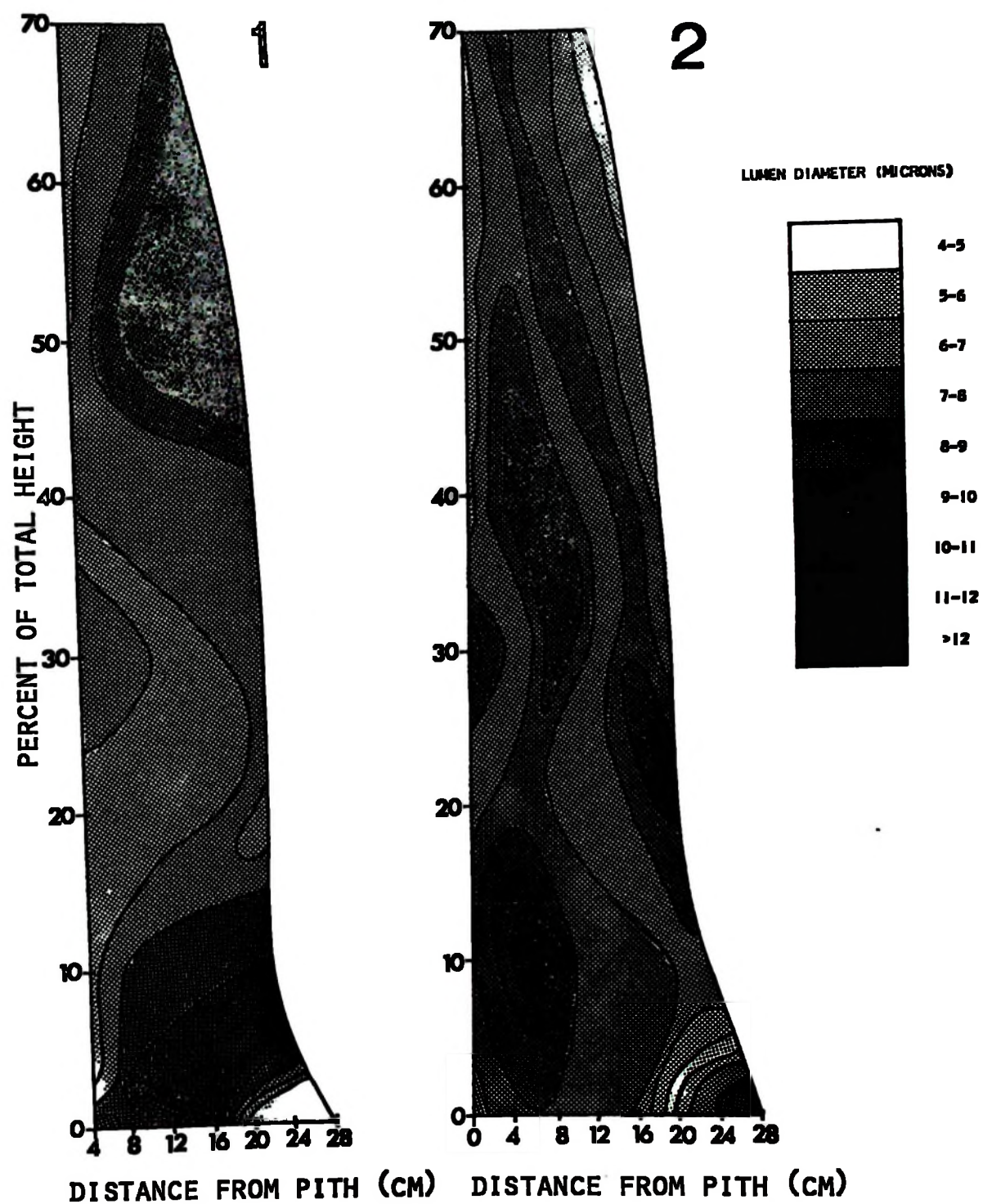


FIGURE 7.3 Variation in fibre lumen diameter in two trees of *E. deglupta*.



FIGURE 7.4. Variation in fibre diameter in two trees of *E. deglupta*

Fibre double wall thickness shows a general increase from pith towards the bark at most height levels. The greatest wall thickness is found in the buttress area and in outer parts of the trunk at the upper levels.

Except in the butt portion, where lumens are very variable; lumen diameter changes only slightly within any one level. However, there are marked differences between height levels.

The fibre diameter diagram is merely a summation of wall thickness and lumen diameter with wall thickness dominant.

These subjective observations are explained objectively by the component analysis where the first component (wall thickness and fibre diameter) is associated with both height and radial distance from pith effects, while the third component (lumen diameter and lumen area) is associated mainly with height effects.

Little comparative information is available from the literature. Stauffer (1892) for *Betula*, Aytug (1962) for *Fagus*, Bamber and Humphreys (1963) for *E. grandis* and Stern-Cohen and Fahn (1964) for *E. gomphocephala* found an increase in fibre diameter from pith to bark. Stern-Cohen and Fahn could not determine a clear centrifugal trend for fibre wall thickness in *E. gomphocephala* while the other workers found increasing wall thickness with distance from the pith in *Betula*, *Fagus* and *E. grandis*.

Stauffer (1892) found that fibre wall thickness decreased with increasing height in *Betula*.

Further information is lacking, as generally only one height level in the trunk has been studied by most workers.

(c) Vessel numbers and size

The variation of vessel number and vessel size in the trunk of *E. deglupta* is illustrated in Figures 7.5 and 7.6. Vessel numbers decrease immediately with increasing distance from the pith but tend to stabilize in the outer growth layers at any one level.

The vessels increase in size with increasing distance from the pith but this pattern is more variable.

The component analysis indicates there is little consistent association with radial distance from the pith and no association with height for these two variables.

An increase in vessel size with distance from the pith (or age) has been recorded by Trendelenburg and Mayer-Wegelin (1955) and Courtois *et al* (1964) in *Quercus*; Krassnitskii (1958) in *Fraxinus*; Clark (1930) in *Ulmus*; Dadswell (1958) and Bamber and Humphreys (1963) in *Eucalyptus*; and Meyer-Uhlenreid (1957) in *Populus*. There is little information on the change with height.

(d) Percentage of tissue types by volume

Figures 7.7, 7.8 and 7.9 show the variation and the proportion of the wood volume occupied by vessels, fibres and rays. Because of the small amount of axial parenchyma present, this was not determined separately but included in the measurements for fibre volume. There is a greater proportion of vessels in the outer layers of the upper part of the trunk than in the lower part near the pith.

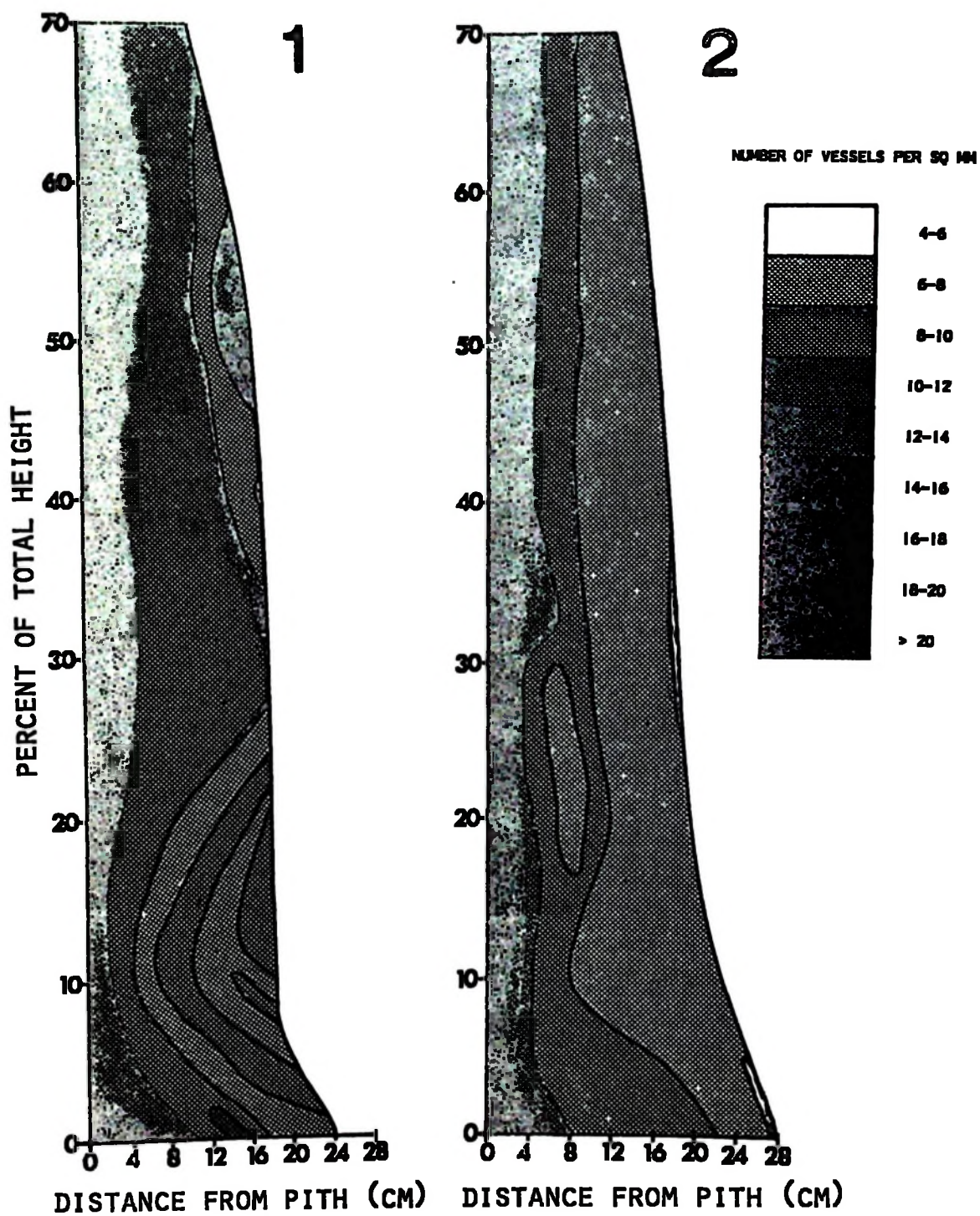


FIGURE 7.5 Variation in number of vessels per unit area of cross-section in two trees of *E. deglupta*.



FIGURE 7.6 Variation in vessel size in two trees of *E. deglupta*. Size of vessels is expressed as the area of their cross-sections in units of $\text{sq mm} \times 10^{-3}$.

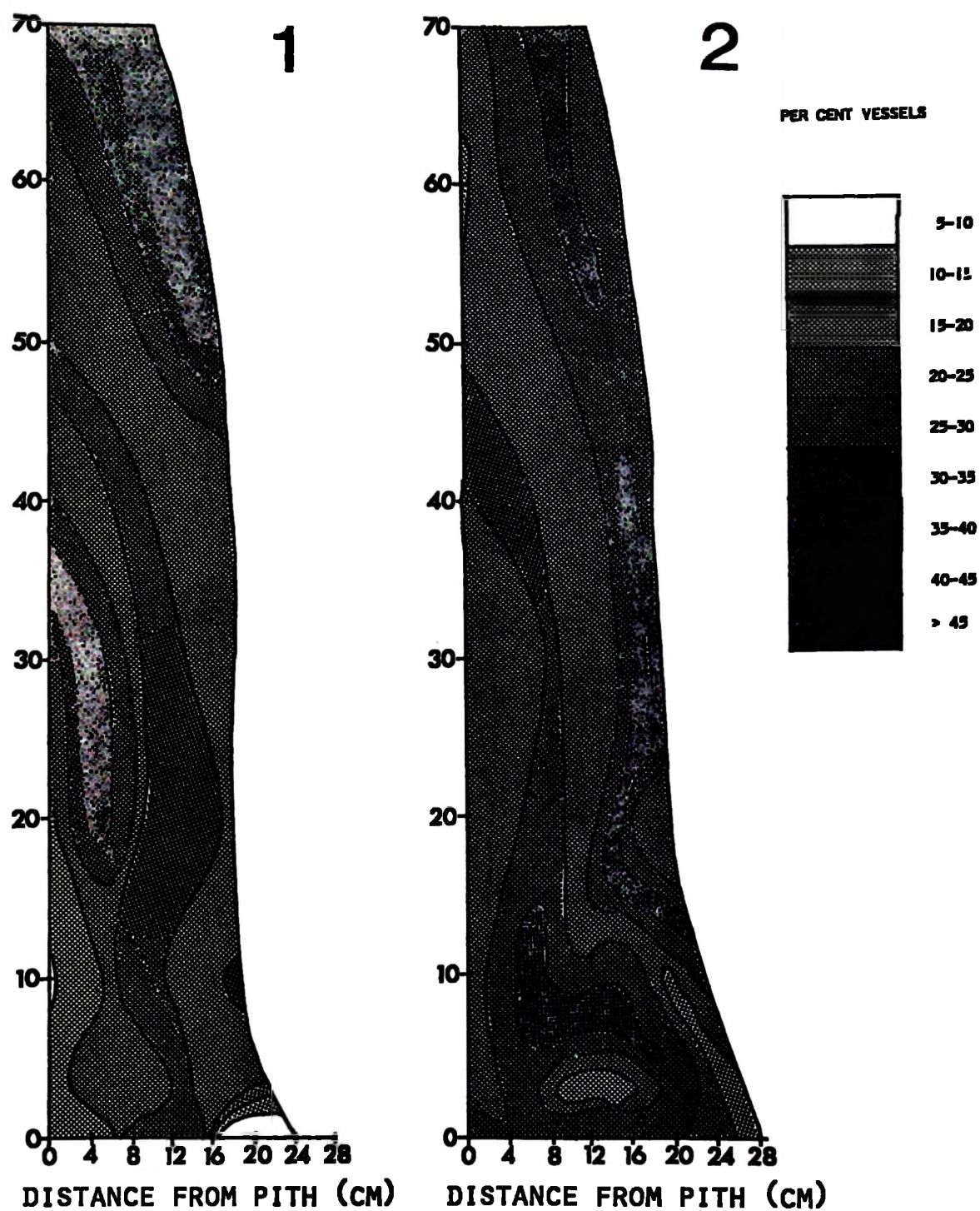


FIGURE 7.7 Variation in the volume of the wood of *E. deglupta* occupied by vessels expressed as a percentage of the total volume.

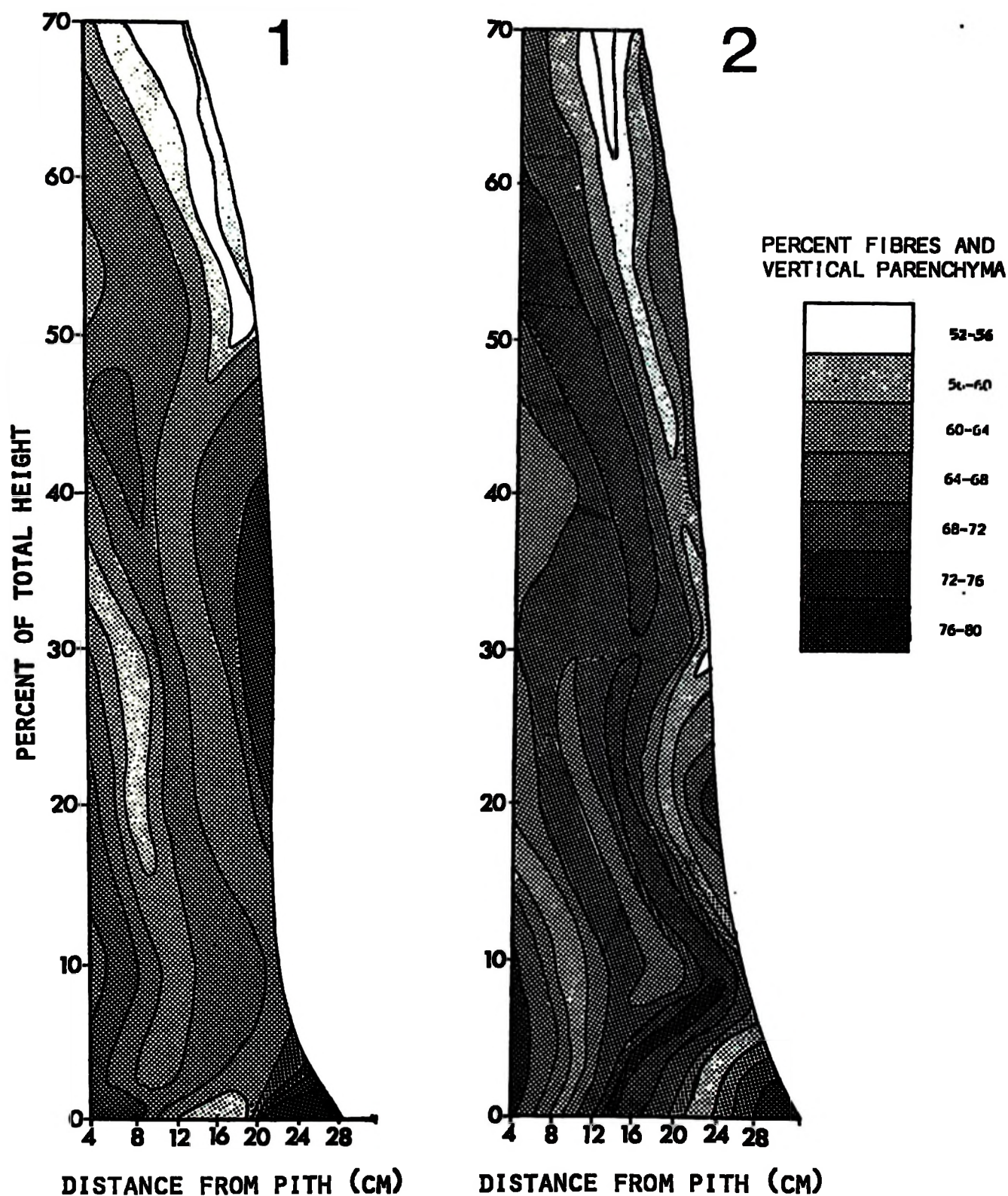


FIGURE 7.8 Variation in the volume of the wood of *E. deglupta* occupied by fibres and vertical parenchyma expressed as a percentage of the total volume.

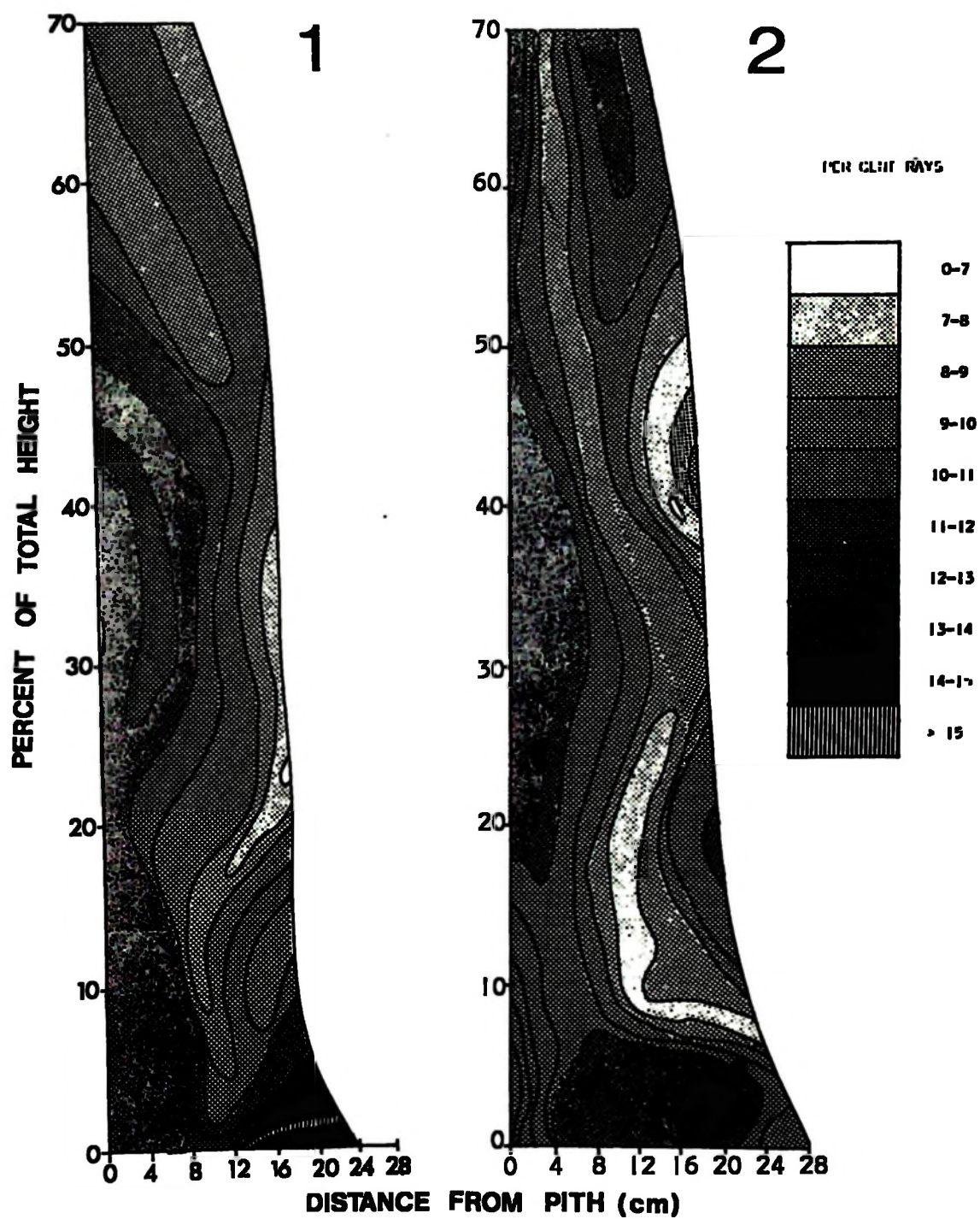


FIGURE 7.9 Variation in the volume of the wood of *E. deglupta* occupied by rays expressed as a percentage of the total volume.

The trend for fibres and rays is not clear because of the complex variation patterns.

The proportion of tissue type appears in the second component of variation which is not associated with within-tree positional effects.

The relation between age or distance from the pith and the relative proportion of tissue types has been little reported.

- In many cases these reports have considered only trees of considerable age (up to 300 years old) with conflicting results.

Investigations have been made on *Quercus* (Schulz, 1959; Courtols, Elling and Busch, 1964), *Fagus* (Linnemann, 1953; Schulz, 1957; Ishida, Horikawa and Mitani, 1963), *Populus* (Jayme, Hindenberg, Harders-Steinhauser and Branscheld, 1943; Scaramuzzi, 1955) and *Eucalyptus* (Scaramuzzi, 1961). Of these, Jayme and co-workers (1943), Linnemann (1953) and Ishid and co-workers (1963) found no significant relationship between proportion of cell types and age or distance from the pith. Schulz (1959) and Courtols and co-workers (1964) found that fibre proportion decreased and vessel proportion increased with increasing distance from the pith. Scaramuzzi (1955) found little variation in the volume proportions of wood elements in a single *Populus x euramericana* (Dode) Guinier Cv. 'I 214' tree from a ten-year-old plantation. His work with eight species of *Eucalyptus* (Scaramuzzi, 1961) was limited to one tree for each species and one sampling height in each tree.

(e) Chemical constituents

Figure 7.10 shows examples of the variation for lignin and extractives in one of the *E. deglupta* trees. The pattern is complex but this is due mainly to the small increment levels chosen for different shading. The principal component analysis indicated that there is no regular variation of these two variables with height or distance from the pith. These variables vary very little in the portion of the stem from 10-40 per cent of final tree height.

The variability of the chemical composition of the wood within trees has been investigated by several workers. Because of a wide diversity of methods of sampling and analysis used, results are not comparable. Usually only the butt level has been examined.

Ferrari (1966) looked at the pith to bark trend of lignin variation at three levels in *Populus x euramerioana* Dode (Guinier) and found little variation from pith to bark and a slight increase from the butt upwards.

(f) Density

Figure 7.11 shows the pattern of density variation in two trees of *E. deglupta*. The patterns are complex with discrete areas of high and low density. Higgs (1969) found similar patterns in *E. regnans*.

The component analysis for the variation in *E. deglupta* wood indicates that density varies systematically with height and distance from the pith. However, this is difficult to visualize for the patterns shown.

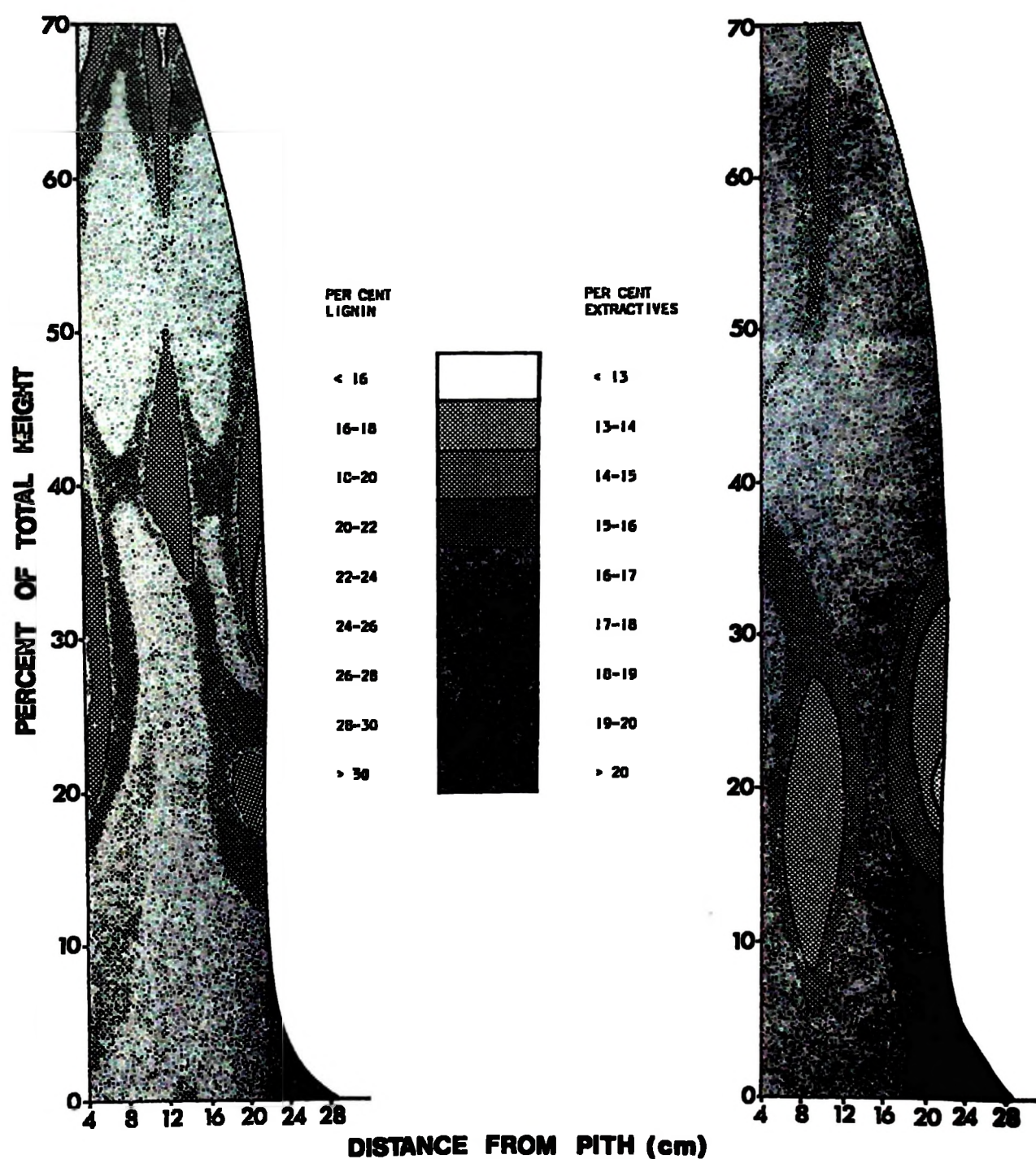


FIGURE 7.10 A. Variation in the percentage lignin content of the wood in one tree of *E. deglupta*. B. Variation in the percentage extractives content of the wood in one tree of *E. deglupta*.

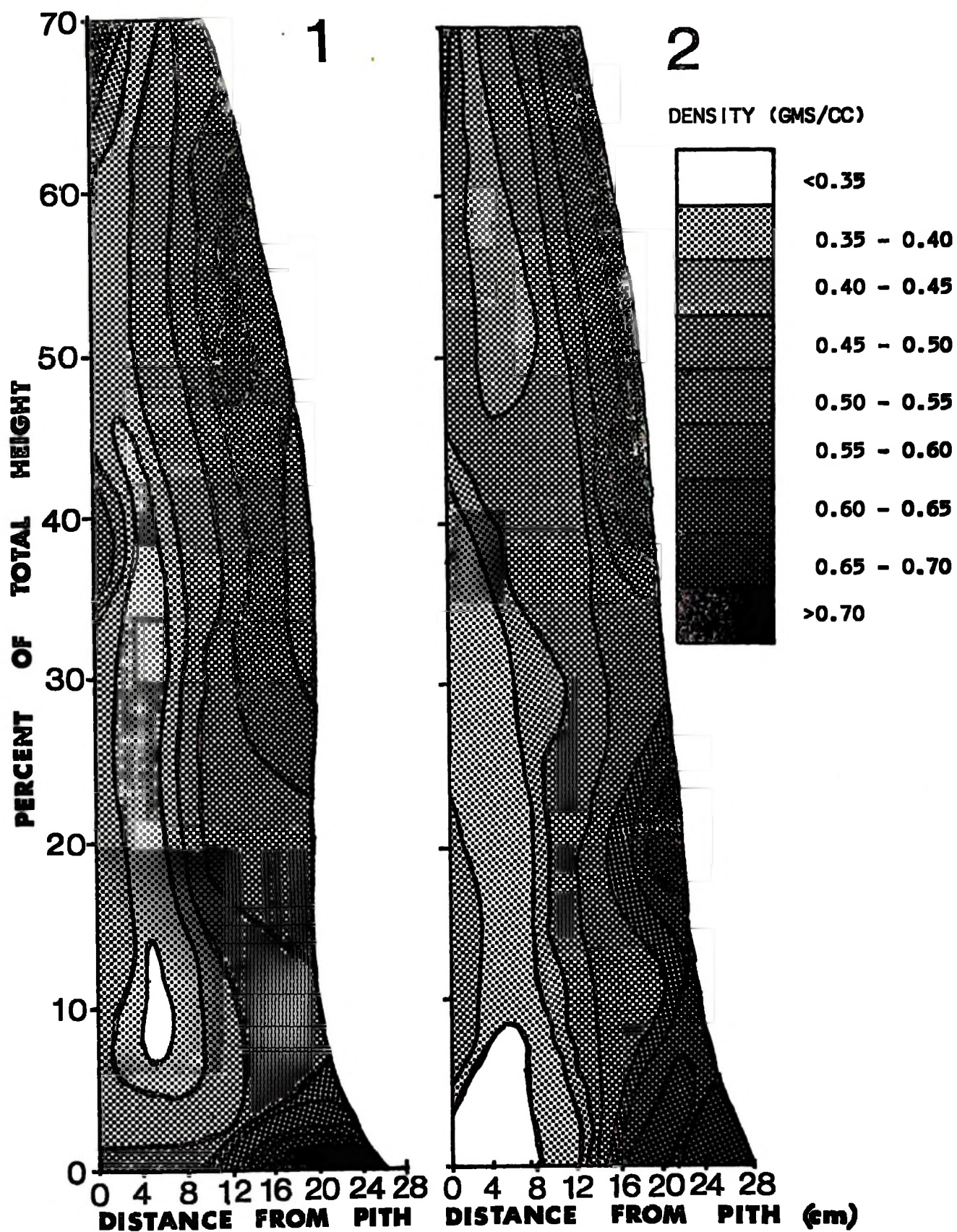


FIGURE 7.11 Variation in the density of the wood of two trees of *E. deglupta*.

In hardwood species the common pattern of radial variation, so far found, has been an increase outwards through the heartwood, e.g., in *Populus tremuloides* (Brown and Valentine, 1962), *Swietenia macrophylla* (Briscoe *et al*, 1963), *Eucalyptus grandis/saligna* (Villiers, 1965), *E. grandis* (Bamber and Humphreys, 1963), *Betula* (Stauffer, 1892).

In contrast a decrease in density radially has been found in some studies, e.g., *Quercus falcata* (Hamilton, 1961), *Quercus sessiflora* (Todorovski, 1961), *Fraxinus*, *Carya*, *Ulmus*, *Quercus*, *Juglans* (Paul, 1963).

Density has been observed to decrease with increasing height in *Acer saccharum* and *Quercus alba* (Myer, 1930).

An increase towards the crown has been observed in *Populus* species (Götze, 1964) and in the lower bole of *E. regnans* (Dargaval, 1968).

A further commonly observed variation pattern with height for hardwoods has been an increase from ground level to the central bole then a decrease into the crown region, e.g., *Quercus sessiflora* (Todorovski, 1961), *Quercus falcata* (Hamilton, 1961), *Swietenia macrophylla* (Briscoe *et al*, 1963), *E. grandis* (Bamber and Humphreys, 1963), *Liquidamber styraciflua* (Webb, 1964) and *Liriodendron tulipifera* (Taylor, 1968 a).

The important features of wood variability have been shown to vary with height and distance from the pith. This means that comparison between trees is very difficult. In characterizing trees in a tree improvement programme sampling is required to be

non-destructive. The next step was to establish if a single bark to pith sample could represent the wood properties of the whole tree.

7.5 SAMPLE REPRESENTATIVENESS

Estimates of the average wood parameters of the whole tree may be calculated either as arithmetic or weighted averages, the latter method assigning proportionally greater weight to observations made at greater distances from the pith.

Bias of the arithmetic average has been discussed by Stokes (1921), but where the objective is to rank trees in order of increasing or decreasing average values, bias is of little importance provided all trees are equally affected.

Generally breast height has been found to be a representative sampling position, hence investigators have rarely examined the differences in representativeness of samples at different height levels.

For comparison of the different levels (discs) in a tree, a single representative disc value must be determined. Two values were derived - the arithmetic disc average value (ADV) and the weighted disc average value (WDV). These values were derived from measurements previously obtained at 5, 25, 45, 65, 85 and 95 per cent of the distance from pith to bark in discs taken at ground level, breast height, 10, 20, 30, 40, 50, 60 and 70 per cent of tree total height in nine *E. deglupta* trees from Keravat, New Britain (Chapters 4 and 6).

$$ADV = \frac{p_{05} + p_{25} + p_{45} + p_{65} + p_{85} + p_{95}}{6}$$

where p_{05} , ..., p_{95} are the values of any parameter measured at the stated radial percentage points.

The *WDV* was derived by assuming each measurement was representative of an annular area which had boundaries corresponding to the mid-points between successive observations. Thus the outer values are given greater weight, as shown in Figure 7.12.

$$WDV = \frac{(p_{05} \times a_{05}) + (p_{25} \times a_{25}) + \dots + (p_{95} \times a_{95})}{A}$$

where a_{05} , ..., a_{95} are areas of the disc represented by each parameter measurement

A = total area of disc

To determine representative whole tree values a similar procedure was followed. Arithmetic whole tree average value (*AWTV*) was derived using the formula

$$AWTV = \frac{\sum_{i=1}^q (ADV)_i}{q}$$

where q = number of discs

Weighted whole tree average value (*WWTV*) was derived as follows, assuming discs were representative of the volume of stem bounded by the mid-points between discs (Figure 7.12).

- p_{05} = distance of percentage sampling point from pith
 a_{05} = area of cross-section on disc represented by a single point sample
 v = volume of log represented by a single sample disc
 A = total area of disc
 V = total volume of tree
 q = number of discs
 $*$ = mid-point between discs
 G.L. = ground level

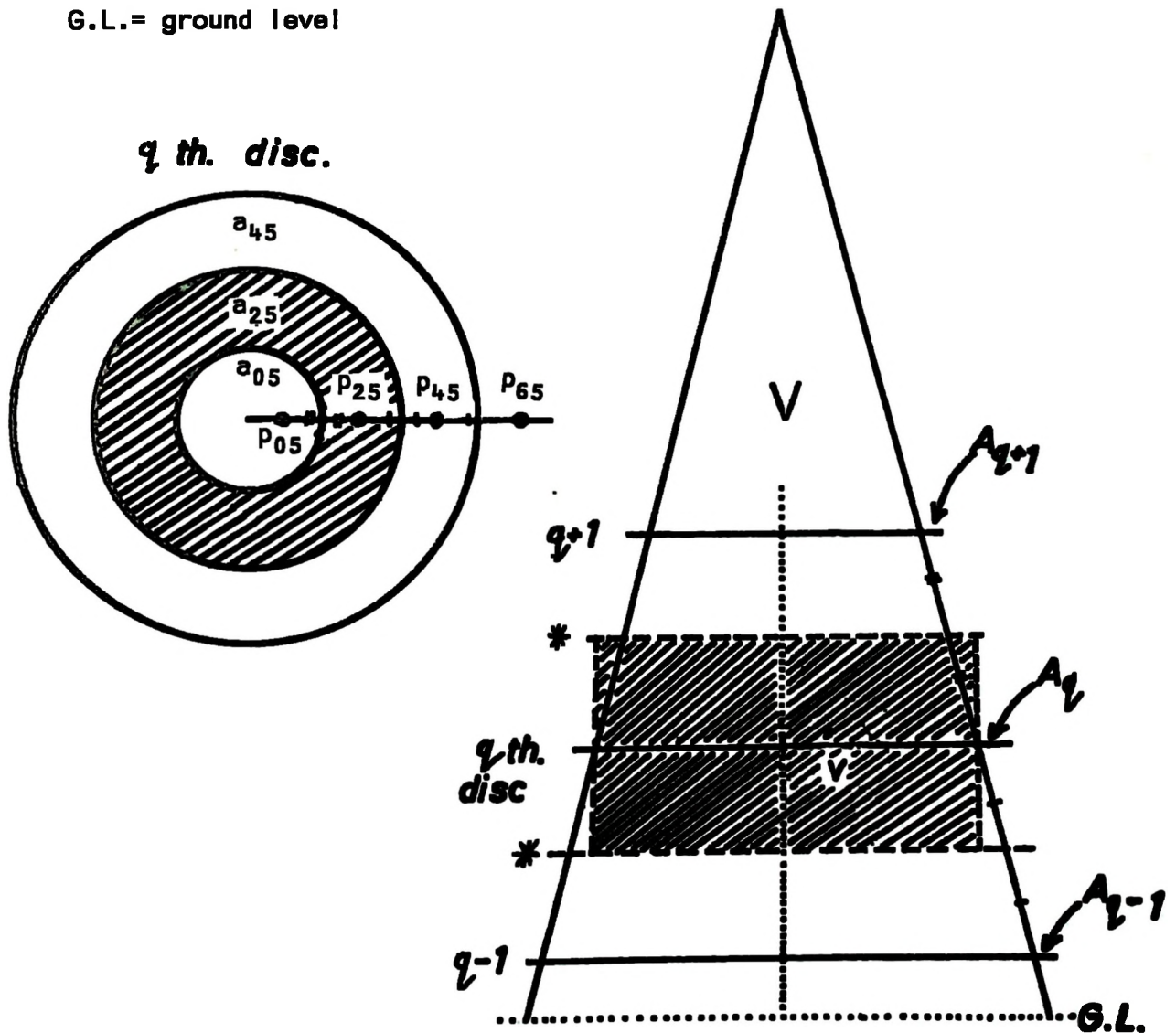


FIGURE 7.12 System of weighting shown diagrammatically.

$$WNTV = \frac{\sum_{i=1}^q (WDV_i \times v_i)}{V}$$

where q = number of discs

V = total volume of stem

v = volume of stem represented by the disc value

These methods were adopted for simplicity although it is recognised that linear variation in radial and vertical directions has been assumed when this is not strictly correct (Tables 7.3 to 7.8).

A standard form of presentation has been adopted for these tables. One section of the table gives the observations, means and standard deviations for arithmetic and weighted disc and whole tree values. The correlation between each of the arithmetic or weighted disc values and each of the arithmetic whole tree or weighted whole tree values is then given. The greater the value of the correlation coefficient and the higher the degree of significance, the more representative is the pith-to-bark sample of the whole tree value. Regressions analysis, assuming linear relationships between disc values and whole tree values, indicates the accuracy of prediction of whole tree values from disc values at the various height levels. The standard errors of estimate of the regressions are directly applicable to the parameter under consideration. Five aspects have to be considered together in deciding the usefulness of a variable for between tree comparisons:

1. The representativeness of the single sample at a particular height (Indicated in Tables 7.3 to 7.8 by the correlation coefficients, their standard errors and significance).

- ii. The sampling error involved when the more representative samples are considered (indicated in Tables 7.3 to 7.8 by the standard errors of the estimate of regressions, the significance of the regressions and the significance of the regression coefficients).
- iii. The measurement error and amount of work involved in the determination of the parameter on the sample (information contained in Chapter 3).
- iv. The difference between whole tree values compared with ii and iii. (If sampling and measurement errors in determination of a parameter approach or are greater than the differences between trees, the parameter is of little use in tree selection.)
- v. The convenience of sampling the standing tree at the representative height (practical limitations require this to be at 10 per cent height or less).

(a) Fibre length

Only one relationship, that between the weighted whole tree value and weighted disc value at 30 per cent height is significant at the 0.01 per cent probability level (Table 7.4). The corresponding standard error of the estimate of regression is ± 0.008 mm. Standard errors of the estimate of regression for other relationships range from 0.010 to 0.017 mm, these being approximately equal to the standard error between the whole tree values, indicating that the regressions are not sensitive enough to indicate between tree differences.

The difficulty of obtaining a representative sample, tedious measurements, low between tree variation and poor ability of fibre length to characterize wood variation in *E. deglupta* (Chapter 4, Table 4.5) means that it will be of little use as a parameter for tree selection in a tree improvement programme.

(b) Fibre-cross-sectional dimensions

The results presented in Table 7.5 indicate that representative fibre diameter measurements are possible only in the lower bole. Weighted whole tree values vary from 13.7 to 15.4 microns (12 per cent of the mean), arithmetic whole tree values vary from 13.2 to 14.6 microns (10 per cent of the mean). Although these are phenotypic and not genotypic differences, little would appear to be gained by individual tree selection. Further, an accuracy of measurement better than four per cent of the mean is difficult to obtain (Chapter 3), yet this represents one-third of the variation in weighted whole tree values and almost half of the variation in arithmetic whole tree values.

Results for fibre double wall thickness are to be found in Table 7.6. Representative values are more extensive, only the upper two discs being non-representative. Between tree weighted whole tree values vary from 5.6 to 7.8 microns (33 per cent of the mean). Between tree arithmetic values vary from 5.2 to 7.0 microns (30 per cent of the mean). Accuracy of measurement is approximately 12 per cent of the mean (Chapter 3) which is equivalent to more than one-third of the variation in weighted and arithmetic value between trees.

TABLE 7.5 CORRELATION AND REGRESSION ANALYSES FOR DISC AND WHOLE TREE FIBRE DIAMETER VALUES

OBSERVATION MATRIX																				
Tree Number	Growth	Height	10		20		30		40		50		60		70		Mean		Variance	
			mm	cm	mm	cm	mm	cm	mm	cm	mm	cm	mm	cm	mm	cm	mm	cm	mm	cm
1	13.8	14.2	15.9	14.3	15.4	13.7	12.8	13.2	12.6	12.8	12.8	12.9	14.4	15.1	14.0	15.0	12.0	12.5	13.3	13.8
2	14.8	15.1	14.7	14.9	15.1	15.0	13.9	14.4	14.8	14.5	14.2	14.7	13.6	14.0	12.7	12.8	13.1	13.2	14.0	14.4
3	13.3	13.7	13.7	14.3	14.1	14.7	14.0	14.5	13.7	14.2	13.7	14.2	13.4	13.6	13.2	13.6	12.8	13.1	13.6	14.2
4	14.4	15.0	14.0	14.5	14.3	15.0	13.7	14.3	13.6	14.1	13.4	13.8	13.4	13.8	13.2	13.6	13.0	13.4	13.7	14.3
5	13.9	14.8	14.2	14.8	14.0	14.6	14.0	14.5	13.8	14.1	13.4	13.8	13.2	13.6	13.2	13.6	13.0	13.4	13.6	14.2
6	13.5	14.0	13.6	14.1	13.5	14.0	13.4	13.8	13.4	13.8	13.2	13.6	12.9	13.1	12.7	13.0	12.7	12.9	13.2	13.7
7	16.9	18.2	16.9	15.7	15.0	15.8	14.3	15.0	14.6	15.4	14.5	15.3	14.5	15.2	13.7	14.2	13.1	13.4	14.6	15.4
8	15.6	16.5	14.7	15.3	14.9	15.3	14.3	15.0	14.3	15.0	13.4	13.7	13.7	14.2	13.3	13.7	13.1	13.4	13.9	14.9
9	14.6	15.4	14.8	15.6	14.9	15.7	14.4	15.0	14.8	14.5	13.7	14.2	13.6	14.1	13.3	13.6	12.8	13.1	13.8	14.4
Mean	14.5	15.2	14.3	14.9	14.3	14.8	13.9	14.4	13.8	14.3	13.6	14.0	13.4	13.8	12.7	13.0	13.1	13.4	13.8	14.4
SD	1.1	1.4	0.5	0.6	0.6	0.7	0.5	0.6	0.7	0.5	0.7	0.5	0.7	0.4	0.7	0.4	0.7	0.4	0.6	0.7
SE																				

CORRELATION AND REGRESSION ANALYSES									
Disc Height	Correlation coefficient (r)		Significance		Equation		F		Significance
	Value	SE	Value	SE	Equation	Equation	Value	SE	Significance
Growth	0.938	0.131	***		$Y = 6.3 + 0.343 X$	$Y = 6.3 + 0.343 X$	11	0.019	***
Growth Height	0.893	0.132	***		$Y = 2.8 + 0.288 X$	$Y = 2.8 + 0.288 X$	11	0.019	***
10 per cent	0.876	0.181	***		$Y = 3.0 + 0.177 X$	$Y = 3.0 + 0.177 X$	11	0.019	***
20 per cent	0.774	0.239	*		$Y = 4.7 + 0.253 X$	$Y = 4.7 + 0.253 X$	11	0.019	***
30 per cent	0.694	0.170	***		$Y = 4.6 + 0.266 X$	$Y = 4.6 + 0.266 X$	11	0.019	***
40 per cent	0.820	0.216	***		$Y = 4.5 + 0.280 X$	$Y = 4.5 + 0.280 X$	11	0.019	***
50 per cent	0.495	0.329	NS		$Y = 6.3 + 0.402 X$	$Y = 6.3 + 0.402 X$	11	0.101	NS
60 per cent	0.173	0.375	NS		$Y = 12.1 + 0.128 X$	$Y = 12.1 + 0.128 X$	11	0.148	NS
70 per cent	0.376	0.369	NS		$Y = 4.7 + 0.712 X$	$Y = 4.7 + 0.712 X$	11	0.144	NS

REGRESSION ANALYSIS BETWEEN MEY (27) AND MEY (21)									
Disc Height	Correlation coefficient (r)		Significance		Equation		F		Significance
	Value	SE	Value	SE	Equation	Equation	Value	SE	Significance
Growth	0.938	0.131	***		$Y = 6.3 + 0.343 X$	$Y = 6.3 + 0.343 X$	11	0.019	***
Growth Height	0.893	0.132	***		$Y = 2.8 + 0.288 X$	$Y = 2.8 + 0.288 X$	11	0.019	***
10 per cent	0.876	0.181	***		$Y = 3.0 + 0.177 X$	$Y = 3.0 + 0.177 X$	11	0.019	***
20 per cent	0.774	0.239	*		$Y = 4.7 + 0.253 X$	$Y = 4.7 + 0.253 X$	11	0.019	***
30 per cent	0.694	0.170	***		$Y = 4.6 + 0.266 X$	$Y = 4.6 + 0.266 X$	11	0.019	***
40 per cent	0.820	0.216	***		$Y = 4.5 + 0.280 X$	$Y = 4.5 + 0.280 X$	11	0.019	***
50 per cent	0.495	0.329	NS		$Y = 6.3 + 0.402 X$	$Y = 6.3 + 0.402 X$	11	0.101	NS
60 per cent	0.173	0.375	NS		$Y = 12.1 + 0.128 X$	$Y = 12.1 + 0.128 X$	11	0.148	NS
70 per cent	0.376	0.369	NS		$Y = 4.7 + 0.712 X$	$Y = 4.7 + 0.712 X$	11	0.144	NS

REGRESSION ANALYSIS BETWEEN MEY (27) AND MEY (21)									
Disc Height	Correlation coefficient (r)		Significance		Equation		F		Significance
	Value	SE	Value	SE	Equation	Equation	Value	SE	Significance
Growth	0.938	0.131	***		$Y = 6.3 + 0.343 X$	$Y = 6.3 + 0.343 X$	11	0.019	***
Growth Height	0.893	0.132	***		$Y = 2.8 + 0.288 X$	$Y = 2.8 + 0.288 X$	11	0.019	***
10 per cent	0.876	0.181	***		$Y = 3.0 + 0.177 X$	$Y = 3.0 + 0.177 X$	11	0.019	***
20 per cent	0.774	0.239	*		$Y = 4.7 + 0.253 X$	$Y = 4.7 + 0.253 X$	11	0.019	***
30 per cent	0.694	0.170	***		$Y = 4.6 + 0.266 X$	$Y = 4.6 + 0.266 X$	11	0.019	***
40 per cent	0.820	0.216	***		$Y = 4.5 + 0.280 X$	$Y = 4.5 + 0.280 X$	11	0.019	***
50 per cent	0.495	0.329	NS		$Y = 6.3 + 0.402 X$	$Y = 6.3 + 0.402 X$	11	0.101	NS
60 per cent	0.173	0.375	NS		$Y = 12.1 + 0.128 X$	$Y = 12.1 + 0.128 X$	11	0.148	NS
70 per cent	0.376	0.369	NS		$Y = 4.7 + 0.712 X$	$Y = 4.7 + 0.712 X$	11	0.144	NS

REGRESSION ANALYSIS BETWEEN MEY (27) AND MEY (21)									
Disc Height	Correlation coefficient (r)		Significance		Equation		F		Significance
	Value	SE	Value	SE	Equation	Equation	Value	SE	Significance
Growth	0.938	0.131	***		$Y = 6.3 + 0.343 X$	$Y = 6.3 + 0.343 X$	11	0.019	***
Growth Height	0.893	0.132	***		$Y = 2.8 + 0.288 X$	$Y = 2.8 + 0.288 X$	11	0.019	***
10 per cent	0.876	0.181	***		$Y = 3.0 + 0.177 X$	$Y = 3.0 + 0.177 X$	11	0.019	***
20 per cent	0.774	0.239	*		$Y = 4.7 + 0.253 X$	$Y = 4.7 + 0.253 X$	11	0.019	***
30 per cent	0.694	0.170	***		$Y = 4.6 + 0.266 X$	$Y = 4.6 + 0.266 X$	11	0.019	***
40 per cent	0.820	0.216	***		$Y = 4.5 + 0.280 X$	$Y = 4.5 + 0.280 X$	11	0.019	***
50 per cent	0.495	0.329	NS		$Y = 6.3 + 0.402 X$	$Y = 6.3 + 0.402 X$	11	0.101	NS
60 per cent	0.173	0.375	NS		$Y = 12.1 + 0.128 X$	$Y = 12.1 + 0.128 X$	11	0.148	NS
70 per cent	0.376	0.369	NS		$Y = 4.7 + 0.712 X$	$Y = 4.7 + 0.712 X$	11	0.144	NS

REGRESSION ANALYSIS BETWEEN MEY (27) AND MEY (21)									
Disc Height	Correlation coefficient (r)		Significance		Equation		F		Significance
	Value	SE	Value	SE	Equation	Equation	Value	SE	Significance
Growth	0.938	0.131	***		$Y = 6.3 + 0.343 X$	$Y = 6.3 + 0.343 X$	11	0.019	***
Growth Height	0.893	0.132	***		$Y = 2.8 + 0.288 X$	$Y = 2.8 + 0.288 X$	11	0.019	***
10 per cent	0.876	0.181	***		$Y = 3.0 + 0.177 X$	$Y = 3.0 + 0.177 X$	11	0.019	***
20 per cent	0.774	0.239	*		$Y = 4.7 + 0.253 X$	$Y = 4.7 + 0.253 X$	11	0.019	***
30 per cent	0.694	0.170	***		$Y = 4.6 + 0.266 X$	$Y = 4.6 + 0.266 X$	11	0.019	***
40 per cent	0.820	0.216	***		$Y = 4.5 + 0.280 X$	$Y = 4.5 + 0.280 X$	11	0.019	***
50 per cent	0.495	0.329	NS		$Y = 6.3 + 0.402 X$	$Y = 6.3 + 0.402 X$	11	0.101	NS
60 per cent	0.173	0.375	NS		$Y = 12.1 + 0.128 X$	$Y = 12.1 + 0.128 X$	11	0.148	NS
70 per cent	0.376	0.369	NS		$Y = 4.7 + 0.712 X$	$Y = 4.7 + 0.712 X$	11	0.144	NS

REGRESSION ANALYSIS BETWEEN MEY (27) AND MEY (21)									
Disc Height	Correlation coefficient (r)		Significance		Equation		F		Significance
	Value	SE	Value	SE	Equation	Equation	Value	SE	Significance
Growth	0.938	0.131	***		$Y = 6.3 + 0.343 X$	$Y = 6.3 + 0.343 X$	11	0.019	***
Growth Height	0.893	0.132	***		$Y = 2.8 + 0.288 X$	$Y = 2.8 + 0.288 X$	11	0.019	***
10 per cent	0.876	0.181	***		$Y = 3.0 + 0.177 X$	$Y = 3.0 + 0.177 X$	11	0.019	***
20 per cent	0.774	0.239	*		$Y = 4.7 + 0.253 X$	$Y = 4.7 + 0.253 X$	11	0.019	***
30 per cent	0.694	0.170	***		$Y = 4.6 + 0.266 X$	$Y = 4.6 + 0.266 X$	11	0.019	***
40 per cent	0.820	0.216	***		$Y = 4.5 + 0.280 X$	$Y = 4.5 + 0.280 X$	11	0.019	***
50 per cent	0.495	0.329	NS		$Y = 6.3 + 0.402 X$	$Y = 6.3 + 0.402 X$	11	0.101	NS
60 per cent	0.173	0.375	NS		$Y = 12.1 + 0.128 X$	$Y = 12.1 + 0.128 X$	11	0.148	NS
70 per cent	0.376	0.369	NS		$Y = 4.7 + 0.712 X$	$Y = 4.7 + 0.712 X$	11	0.144	NS

REGRESSION ANALYSIS BETWEEN MEY (27) AND MEY (21)									
Disc Height	Correlation coefficient (r)		Significance		Equation		F		Significance
	Value	SE	Value	SE	Equation	Equation	Value	SE	Significance
Growth	0.938	0.131	***		$Y = 6.3 + 0.343 X$	$Y = 6.3 + 0.343 X$	11	0.019	***
Growth Height	0.893	0.132	***		$Y = 2.8 + 0.288 X$	$Y = 2.8 + 0.288 X$	11	0.019	***
10 per cent	0.876	0.181	***		$Y = 3.0 + 0.177 X$	$Y = 3.0 + 0.177 X$	11	0.019	***
20 per cent	0.774	0.239	*		$Y = 4.7 + 0.253 X$	$Y = 4.7 + 0.253 X$	11	0.019	***
30 per cent	0.694	0.170	***		$Y = 4.6 + 0.266 X$	$Y = 4.6 + 0.266 X$	11	0.019	***
40 per cent	0.820	0.216	***		$Y = 4.5 + 0.280 X$	$Y = 4.5 + 0.280 X$	11	0.019	***
50 per cent	0.495	0.329	NS		$Y = 6.3 + 0.402 X$	$Y = 6.3 + 0.402 X$	11	0.101	NS
60 per cent	0.173	0.375	NS		$Y = 12.1 + 0.128 X$	$Y = 12.1 + 0.128 X$	11	0.148	NS
70 per cent	0.376	0.369	NS		$Y = 4.7 + 0.712 X$	$Y = 4.7 + 0.712 X$	11	0.144	NS

Both fibre diameter and fibre double wall thickness have been shown to be important in describing some 60 per cent of the variation in *E. deglupta* wood (Table 4.5). The problem of capitalizing on the considerable phenotypic variation in these features is the difficulty of measurement of the small fibre dimensions.

Ratios including at least one of fibre double wall thickness or fibre diameter could be expected to behave similarly.

The statistics for lumen diameter are given in Table 7.7. Variation between trees is about eight per cent while measurement error is about six per cent. No representative sampling point for whole tree value was evident. This means that the third component (see Table 4.5) featuring fibre lumen dimension and representing some 12 per cent of the variation in the wood of *E. deglupta* cannot be estimated from a single pith to bark sample taken anywhere in the bole below 70 per cent of total tree height.

(c) Vessel size (cross-sectional area)

Arithmetic disc values of vessel size are significantly correlated with arithmetic whole tree values for only the ground level and the 20, 30, 40 and 50 per cent height discs (Table 7.8). Weighted disc values are significantly correlated with weighted whole tree values up to the 30 per cent height level only. Weighted whole tree vessel size ranges from 0.024 to 0.031 sq mm (23 per cent of the mean). Arithmetic whole tree values range from 0.025 to 0.033 sq mm (28 per cent of the mean).

Vessel size occurs in the second component (Table 4.5) representing about 19 per cent of the wood variability in *E. deglupta* and is, therefore, quite important but tedious to

TABLE 7.7 CORRELATION AND REGRESSION ANALYSES FOR DISC AND WHOLE TREE FIBRE LUMEN DIAMETER VALUES

CORRELATION MATRIX																				
Tree Number	Ground	Brest Height	10		20		30		40		50		60		70		Whole tree value			
			ADP	MP	ADP	MP	ADP	MP	ADP	MP	ADP	MP	ADP	MP	ADP	MP	ADP	MP		
1	0.2	0.0	0.4	0.3	0.1	0.3	1.1	7.0	6.9	6.7	7.5	7.4	9.0	9.3	0.3	9.0	7.5	7.0	7.0	0.0
2	0.1	7.0	0.1	7.0	0.2	0.0	0.2	0.2	0.4	0.5	0.2	0.2	7.5	7.5	0.0	0.0	7.0	6.0	0.0	0.0
3	0.0	0.0	7.0	7.0	0.0	0.1	0.0	0.1	7.0	7.0	7.0	7.0	7.0	7.0	0.0	0.0	7.0	0.1	7.0	0.0
4	0.2	0.1	-0.3	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.5	7.4	7.5	7.5	7.0	7.0	7.0	7.0
5	7.0	7.0	0.2	0.2	0.1	0.1	0.2	0.0	0.0	0.0	0.0	0.1	0.0	0.0	7.0	7.0	7.0	7.7	0.0	0.1
6	7.0	7.0	0.0	0.0	0.0	0.1	0.2	0.2	0.1	0.1	0.1	0.3	0.3	0.1	0.2	0.0	0.0	0.1	0.1	0.1
7	7.4	7.2	0.1	0.1	7.0	7.7	7.5	7.7	7.5	7.1	7.7	7.7	7.5	7.6	7.7	7.7	7.7	7.0	7.7	7.0
8	7.7	7.5	7.0	7.0	7.0	7.0	7.7	7.7	7.7	7.7	7.7	7.0	7.0	7.0	7.5	7.0	7.5	7.0	7.7	7.7
9	7.0	7.7	0.0	7.0	0.1	0.2	0.1	0.2	0.3	0.2	7.0	7.0	0.0	0.4	0.1	0.2	7.0	0.0	0.0	0.1
Mean	7.0	7.0	0.1	0.1	0.1	0.1	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.7	7.0	7.0
SE	0.3	0.3	0.3	0.3	0.4	0.3	0.4	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.4	0.1	0.2
CORRELATION AND REGRESSION ANALYSES																				
Disc Height	Correlation coefficient (r) between ADP and MP		Value	SE _r	Significance	Equation	SE _r	SE _r	Variance Ratio	Significance	Equation	SE _r	SE _r	Variance Ratio	Significance					
	Value	SE _r														Significance	Equation	SE _r	SE _r	Variance Ratio
Ground	0.303	0.377	NS			$Z = 5.0 + 0.263 Z$	0.005	2.357	NS	NS	$Z = 4.0 + 0.403 Z$	0.007	0.103	5.172	NS	NS				
Brest Height	0.070	0.371	NS			$Z = 7.5 + 0.020 Z$	0.102	0.020	NS	NS	$Z = 7.0 + 0.023 Z$	0.007	0.103	0.007	NS	NS				
10 per cent	0.379	0.390	NS			$Z = 6.9 + 0.170 Z$	0.045	1.172	NS	NS	$Z = 5.1 + 0.354 Z$	0.006	0.006	4.008	NS	NS				
20 per cent	0.405	0.346	NS			$Z = 6.6 + 0.150 Z$	0.051	1.372	NS	NS	$Z = 6.3 + 0.179 Z$	0.061	1.209	0.061	NS	NS				
30 per cent	0.406	0.330	NS			$Z = 6.8 + 0.144 Z$	0.037	2.102	NS	NS	$Z = 6.4 + 0.176 Z$	0.043	2.360	0.043	NS	NS				
40 per cent	0.322	0.327	NS			$Z = 5.3 + 0.331 Z$	0.077	2.017	NS	NS	$Z = 5.0 + 0.368 Z$	0.087	2.555	0.087	NS	NS				
50 per cent	0.534	0.350	NS			$Z = 6.7 + 0.147 Z$	0.033	2.765	NS	NS	$Z = 6.7 + 0.140 Z$	0.038	2.403	0.038	NS	NS				
60 per cent	0.368	0.364	NS			$Z = 7.3 + 0.081 Z$	0.041	0.341	NS	NS	$Z = 7.2 + 0.080 Z$	0.042	0.436	0.042	NS	NS				
70 per cent	0.288	0.370	NS			$Z = 7.2 + 0.091 Z$	0.061	0.316	NS	NS	$Z = 7.0 + 0.096 Z$	0.067	0.096	0.067	NS	NS				

ADP = Arithmetic disc value

MP = Weighted disc value

ADP = Arithmetic whole tree value

MP = Weighted whole tree value

* $p < 0.05$, $p < 0.01$, $p < 0.001$ significant at five per cent probability level** $p < 0.001$, $p < 0.0001$ significant at one per cent probability level*** $p < 0.0001$, $p < 0.00001$ significant at 0.1 per cent probability level

SE = standard deviation

NS = not significant

number of degrees of freedom for statistical tests = 7

SE = standard error of whole tree value

SE_r = standard error of the estimate of correlation coefficientSE_r = standard error of estimate of regressionSE_r = standard error of estimate of regressionSE_r = standard error of estimate of regressionSE_r = standard error of estimate of regressionSE_r = standard error of estimate of regressionSE_r = standard error of estimate of regressionSE_r = standard error of estimate of regressionSE_r = standard error of estimate of regressionSE_r = standard error of estimate of regressionSE_r = standard error of estimate of regressionSE_r = standard error of estimate of regressionSE_r = standard error of estimate of regressionSE_r = standard error of estimate of regressionSE_r = standard error of estimate of regressionSE_r = standard error of estimate of regressionSE_r = standard error of estimate of regression

TABLE 7.8 CORRELATION AND REGRESSION ANALYSES FOR DISC AND WHOLE TREE VESSEL SIZE VALUES

CORRELATION MATRIX																
Tree Number	Ground	Stem	Height	10 per cent	20 per cent	30 per cent	40 per cent	50 per cent	60 per cent	70 per cent	80 per cent	90 per cent	100 per cent	110 per cent	120 per cent	130 per cent
1	0.020	0.023	0.025	0.027	0.029	0.031	0.033	0.035	0.037	0.039	0.041	0.043	0.045	0.047	0.049	0.051
2	0.025	0.028	0.030	0.032	0.034	0.036	0.038	0.040	0.042	0.044	0.046	0.048	0.050	0.052	0.054	0.056
3	0.030	0.033	0.035	0.037	0.039	0.041	0.043	0.045	0.047	0.049	0.051	0.053	0.055	0.057	0.059	0.061
4	0.035	0.038	0.040	0.042	0.044	0.046	0.048	0.050	0.052	0.054	0.056	0.058	0.060	0.062	0.064	0.066
5	0.040	0.043	0.045	0.047	0.049	0.051	0.053	0.055	0.057	0.059	0.061	0.063	0.065	0.067	0.069	0.071
6	0.045	0.048	0.050	0.052	0.054	0.056	0.058	0.060	0.062	0.064	0.066	0.068	0.070	0.072	0.074	0.076
7	0.050	0.053	0.055	0.057	0.059	0.061	0.063	0.065	0.067	0.069	0.071	0.073	0.075	0.077	0.079	0.081
8	0.055	0.058	0.060	0.062	0.064	0.066	0.068	0.070	0.072	0.074	0.076	0.078	0.080	0.082	0.084	0.086
9	0.060	0.063	0.065	0.067	0.069	0.071	0.073	0.075	0.077	0.079	0.081	0.083	0.085	0.087	0.089	0.091
10	0.065	0.068	0.070	0.072	0.074	0.076	0.078	0.080	0.082	0.084	0.086	0.088	0.090	0.092	0.094	0.096
11	0.070	0.073	0.075	0.077	0.079	0.081	0.083	0.085	0.087	0.089	0.091	0.093	0.095	0.097	0.099	0.101
12	0.075	0.078	0.080	0.082	0.084	0.086	0.088	0.090	0.092	0.094	0.096	0.098	0.100	0.102	0.104	0.106
13	0.080	0.083	0.085	0.087	0.089	0.091	0.093	0.095	0.097	0.099	0.101	0.103	0.105	0.107	0.109	0.111
14	0.085	0.088	0.090	0.092	0.094	0.096	0.098	0.100	0.102	0.104	0.106	0.108	0.110	0.112	0.114	0.116
15	0.090	0.093	0.095	0.097	0.099	0.101	0.103	0.105	0.107	0.109	0.111	0.113	0.115	0.117	0.119	0.121
16	0.095	0.098	0.100	0.102	0.104	0.106	0.108	0.110	0.112	0.114	0.116	0.118	0.120	0.122	0.124	0.126
17	0.100	0.103	0.105	0.107	0.109	0.111	0.113	0.115	0.117	0.119	0.121	0.123	0.125	0.127	0.129	0.131
18	0.105	0.108	0.110	0.112	0.114	0.116	0.118	0.120	0.122	0.124	0.126	0.128	0.130	0.132	0.134	0.136
19	0.110	0.113	0.115	0.117	0.119	0.121	0.123	0.125	0.127	0.129	0.131	0.133	0.135	0.137	0.139	0.141
20	0.115	0.118	0.120	0.122	0.124	0.126	0.128	0.130	0.132	0.134	0.136	0.138	0.140	0.142	0.144	0.146
21	0.120	0.123	0.125	0.127	0.129	0.131	0.133	0.135	0.137	0.139	0.141	0.143	0.145	0.147	0.149	0.151
22	0.125	0.128	0.130	0.132	0.134	0.136	0.138	0.140	0.142	0.144	0.146	0.148	0.150	0.152	0.154	0.156
23	0.130	0.133	0.135	0.137	0.139	0.141	0.143	0.145	0.147	0.149	0.151	0.153	0.155	0.157	0.159	0.161
24	0.135	0.138	0.140	0.142	0.144	0.146	0.148	0.150	0.152	0.154	0.156	0.158	0.160	0.162	0.164	0.166
25	0.140	0.143	0.145	0.147	0.149	0.151	0.153	0.155	0.157	0.159	0.161	0.163	0.165	0.167	0.169	0.171
26	0.145	0.148	0.150	0.152	0.154	0.156	0.158	0.160	0.162	0.164	0.166	0.168	0.170	0.172	0.174	0.176
27	0.150	0.153	0.155	0.157	0.159	0.161	0.163	0.165	0.167	0.169	0.171	0.173	0.175	0.177	0.179	0.181
28	0.155	0.158	0.160	0.162	0.164	0.166	0.168	0.170	0.172	0.174	0.176	0.178	0.180	0.182	0.184	0.186
29	0.160	0.163	0.165	0.167	0.169	0.171	0.173	0.175	0.177	0.179	0.181	0.183	0.185	0.187	0.189	0.191
30	0.165	0.168	0.170	0.172	0.174	0.176	0.178	0.180	0.182	0.184	0.186	0.188	0.190	0.192	0.194	0.196
31	0.170	0.173	0.175	0.177	0.179	0.181	0.183	0.185	0.187	0.189	0.191	0.193	0.195	0.197	0.199	0.201
32	0.175	0.178	0.180	0.182	0.184	0.186	0.188	0.190	0.192	0.194	0.196	0.198	0.200	0.202	0.204	0.206
33	0.180	0.183	0.185	0.187	0.189	0.191	0.193	0.195	0.197	0.199	0.201	0.203	0.205	0.207	0.209	0.211
34	0.185	0.188	0.190	0.192	0.194	0.196	0.198	0.200	0.202	0.204	0.206	0.208	0.210	0.212	0.214	0.216
35	0.190	0.193	0.195	0.197	0.199	0.201	0.203	0.205	0.207	0.209	0.211	0.213	0.215	0.217	0.219	0.221
36	0.195	0.198	0.200	0.202	0.204	0.206	0.208	0.210	0.212	0.214	0.216	0.218	0.220	0.222	0.224	0.226
37	0.200	0.203	0.205	0.207	0.209	0.211	0.213	0.215	0.217	0.219	0.221	0.223	0.225	0.227	0.229	0.231
38	0.205	0.208	0.210	0.212	0.214	0.216	0.218	0.220	0.222	0.224	0.226	0.228	0.230	0.232	0.234	0.236
39	0.210	0.213	0.215	0.217	0.219	0.221	0.223	0.225	0.227	0.229	0.231	0.233	0.235	0.237	0.239	0.241
40	0.215	0.218	0.220	0.222	0.224	0.226	0.228	0.230	0.232	0.234	0.236	0.238	0.240	0.242	0.244	0.246
41	0.220	0.223	0.225	0.227	0.229	0.231	0.233	0.235	0.237	0.239	0.241	0.243	0.245	0.247	0.249	0.251
42	0.225	0.228	0.230	0.232	0.234	0.236	0.238	0.240	0.242	0.244	0.246	0.248	0.250	0.252	0.254	0.256
43	0.230	0.233	0.235	0.237	0.239	0.241	0.243	0.245	0.247	0.249	0.251	0.253	0.255	0.257	0.259	0.261
44	0.235	0.238	0.240	0.242	0.244	0.246	0.248	0.250	0.252	0.254	0.256	0.258	0.260	0.262	0.264	0.266
45	0.240	0.243	0.245	0.247	0.249	0.251	0.253	0.255	0.257	0.259	0.261	0.263	0.265	0.267	0.269	0.271
46	0.245	0.248	0.250	0.252	0.254	0.256	0.258	0.260	0.262	0.264	0.266	0.268	0.270	0.272	0.274	0.276
47	0.250	0.253	0.255	0.257	0.259	0.261	0.263	0.265	0.267	0.269	0.271	0.273	0.275	0.277	0.279	0.281
48	0.255	0.258	0.260	0.262	0.264	0.266	0.268	0.270	0.272	0.274	0.276	0.278	0.280	0.282	0.284	0.286
49	0.260	0.263	0.265	0.267	0.269	0.271	0.273	0.275	0.277	0.279	0.281	0.283	0.285	0.287	0.289	0.291
50	0.265	0.268	0.270	0.272	0.274	0.276	0.278	0.280	0.282	0.284	0.286	0.288	0.290	0.292	0.294	0.296
51	0.270	0.273	0.275	0.277	0.279	0.281	0.283	0.285	0.287	0.289	0.291	0.293	0.295	0.297	0.299	0.301
52	0.275	0.278	0.280	0.282	0.284	0.286	0.288	0.290	0.292	0.294	0.296	0.298	0.300	0.302	0.304	0.306
53	0.280	0.283	0.285	0.287	0.289	0.291	0.293	0.295	0.297	0.299	0.301	0.303	0.305	0.307	0.309	0.311
54	0.285	0.288	0.290	0.292	0.294	0.296	0.298	0.300	0.302	0.304	0.306	0.308	0.310	0.312	0.314	0.316
55	0.290	0.293	0.295	0.297	0.299	0.301	0.303	0.305	0.307	0.309	0.311	0.313	0.315	0.317	0.319	0.321
56	0.295	0.298	0.300	0.302	0.304	0.306	0.308	0.310	0.312	0.314	0.316	0.318	0.320	0.322	0.324	0.326
57	0.300	0.303	0.305	0.307	0.309	0.311	0.313	0.315	0.317	0.319	0.321	0.323	0.325	0.327	0.329	0.331
58	0.305	0.308	0.310	0.312	0.314	0.316	0.318	0.320	0.322	0.324	0.326	0.328	0.330	0.332	0.334	0.336
59	0.310	0.313	0.315	0.317	0.319	0.321	0.323	0.325	0.327	0.329	0.331	0.333	0.335	0.337	0.339	0.341
60	0.315	0.318	0.320	0.322	0.324	0.326	0.328	0.330	0.332	0.334	0.336	0.338	0.340	0.342	0.344	0.346
61	0.320	0.323	0.325	0.327	0.329	0.331	0.333	0.335	0.337	0.339	0.341	0.343	0.345	0.347	0.349	0.351
62	0.325	0.328	0.330	0.332	0.334	0.336	0.338	0.340	0.342	0.344	0.346	0.348	0.350	0.352	0.354	0.356
63	0.330	0.333	0.335	0.337	0.339	0.341	0.343	0.345	0.347	0.349	0.351	0.353	0.355	0.357	0.359	0.361
64	0.335	0.338	0.340	0.342	0.344	0.346	0.348	0.350	0.352	0.354	0.356	0.358	0.360	0.362	0.364	0.366
65	0.340	0.343	0.345	0.347	0.349	0.351	0.353	0.355	0.357	0.359	0.361	0.363	0.365	0.367	0.369	0.371
66	0.345	0.348	0.350	0.352	0.354	0.356	0.358	0.360	0.362	0.364	0.366	0.368	0.370	0.372	0.374	0.376
67	0.350	0.353	0.355	0.357	0.359	0.361	0.363	0.365	0.367	0.369	0.371	0.373	0.375	0.377	0.379	0.381
68	0.355	0.358	0.360	0.362	0.364	0.366	0.368	0.370	0.372	0.374	0.376	0.378	0.380	0.382	0.384	0.386
69	0.360	0.363	0.365	0.367	0.369	0.371	0.373	0.375	0.377	0.379	0.381	0.383	0.385	0.387	0.389	0.391
70	0.365	0.368														

measure (Chapter 3). The area of vessels could be measured directly or as was done in this study, the percentage vessels by volume and number of vessels per unit area of cross-section could be obtained separately and average vessel size derived.

So far, examples have been given for at least one variable which features prominently in each of the four components of the principal component model of wood variability for *E. deglupta* (Chapter 4). All are either tedious to measure accurately or, when determined on only one bark to pith sample, at a particular height, are not representative of the whole tree value for selection purposes (Table 7.9).

(d) Wood density

Both arithmetic disc density and weighted disc density values are representative of the respective whole tree values, provided sampling is carried out between about the 10 and 50 per cent height levels (Table 7.10). The most representative disc is at 20 per cent height ($r > 0.90$, significant at the 0.1 per cent level). The values for arithmetic whole tree density range from 0.448 to 0.550 gms/cc (determined by X-ray densitometry). This range represents 20 per cent of the mean, while the standard error of estimate of the value derived from the ten per cent disc is ± 0.009 gms/cc, only two per cent of the mean. The values for weighted whole tree density range from 0.447 to 0.574 gms/cc. This range represents 25 per cent of the between-tree mean while the standard error of estimate from the disc at ten per cent height is 0.010 gms/cc, or two per cent of the mean between trees.

TABLE 7.9 COMPARISON OF WITHIN= AND BETWEEN= TREE VARIABILITY, PHENOTYPIC RANGE AND PRECISION*

MEASUREMENT OF TWENTY-FOUR PARAMETERS[†]

Parameter	Units	Standard Deviation		Phenotypic Statistics			Precision of Measurement*	
		Within Trees	Between Trees	Mean	Range	Range as Per cent of Mean	Value	Per cent of Mean
x ₁	mm	0.187	0.052	1.069	0.996-1.160	15.3	±0.032	3.0 +
x ₂	microns	0.116	0.7	6.5	5.6-7.8	33.8	0.5	7.7 φ
x ₃	microns	0.116	0.2	7.9	7.6-8.1	6.3	0.5	6.3 +
x ₄	microns	0.149	0.6	14.4	13.7-15.4	11.8	0.5	3.5 φ
x ₅	per cent	2.04	0.6	9.5	8.8-10.4	16.8	2.0	21.1 +
x ₆	per cent	4.88	2.2	66.0	63.4-70.4	10.6	5.0	7.6 o
x ₇	per cent	8.61	2.5	24.7	20.0-28.0	32.4	5.0	20.2 +
x ₈	No/mm ²	2.09	0.4	8.3	7.5-8.9	16.9	2.0	24.1 o
x ₉	mm ²	0.009	0.003	0.030	0.027-0.034	23.3	0.003	10.0 +
x ₁₀	ratio	11.07	4.5	74.6	66.7-80.2	18.1	-	- +
x ₁₁	ratio	0.249	0.03	0.44	0.40-0.50	22.7	-	- o
x ₁₂	ratio	0.068	0.03	0.56	0.50-0.60	17.9	-	- o
x ₁₃	ratio	0.067	0.03	0.70	0.66-0.73	10.0	-	- o
x ₁₄	No/mm	8.56	11.0	82	73-104	37.8	2.0	2.4 φ
x ₁₅	microns ²	8.62	17.0	126	108-160	41.3	16.0	12.7 φ
x ₁₆	microns ²	11.00	15.0	181	165-209	24.3	13.0	7.2 φ
x ₁₇	microns ²	5.1	3.0	56	51-58	12.5	7.0	12.5 o
x ₁₈	ratio	0.075	0.03	0.69	0.64-0.75	15.9	-	- o
x ₁₉	ratio	0.177	0.07	0.47	0.35-0.56	44.7	-	- o
x ₂₀	ratio	0.075	0.03	0.31	0.25-0.36	35.5	-	- o
x ₂₁	No/mm ²	14.2	41.7	571	499-624	21.9	30.0	5.2 φ
x ₂₂	per cent	4.1	1.8	24.1	22.2-27.3	21.2	0.5	2.1 o
x ₂₃	per cent	1.7	0.9	17.4	16.4-19.0	14.9	0.5	2.9 o
x ₂₄	per cent	5.1	2.6	58.4	53.6-61.1	12.8	0.5	0.9 o

[†]For names of parameters, see Table 4.1 on page 69. *At 95 per cent confidence level.

+ Not well represented by a single sample at ten per cent height. o Within-tree variability greater than between tree variability. φ Between-tree variability much greater than within-tree variability and adequately represented by a single sample at ten per cent height; thus these are suitable parameters for use in a selection programme.

TABLE 7.10 CORRELATION AND REGRESSION ANALYSES FOR DISC AND WHOLE TREE DENSITY VALUES

OBSERVATION MATRIX															
Tree Number	Ground	Stem Height	10 per cent	20 per cent	30 per cent	40 per cent	50 per cent	60 per cent	70 per cent	Whole tree value					
	ABY	ABY	ABY	ABY	ABY	ABY	ABY	ABY	ABY	ABY	ABY	ABY	ABY	ABY	ABY
1	0.370	0.403	0.476	0.498	0.418	0.430	0.460	0.508	0.489	0.517	0.496	0.510	0.534	0.543	0.499
2	0.472	0.530	0.475	0.531	0.475	0.503	0.472	0.502	0.468	0.481	0.500	0.537	0.513	0.536	0.485
3	0.498	0.464	0.508	0.523	0.472	0.462	0.477	0.479	0.468	0.502	0.478	0.483	0.487	0.481	0.473
4	0.487	0.323	0.498	0.471	0.460	0.498	0.460	0.481	0.472	0.506	0.523	0.546	0.520	0.574	0.481
5	0.434	0.469	0.508	0.508	0.497	0.418	0.481	0.430	0.438	0.456	0.458	0.464	0.457	0.467	0.448
6	0.518	0.543	0.478	0.509	0.468	0.456	0.419	0.432	0.420	0.418	0.455	0.469	0.423	0.439	0.470
7	0.377	0.438	0.441	0.454	0.469	0.530	0.519	0.556	0.433	0.486	0.536	0.573	0.575	0.596	0.531
8	0.548	0.588	0.508	0.591	0.511	0.543	0.546	0.582	0.533	0.581	0.572	0.596	0.569	0.587	0.588
9	0.583	0.433	0.588	0.541	0.474	0.454	0.483	0.493	0.477	0.498	0.598	0.573	0.413	0.413	0.487
Mean	0.513	0.508	0.470	0.497	0.461	0.477	0.473	0.498	0.489	0.519	0.508	0.527	0.523	0.540	0.508
SD	0.097	0.085	0.060	0.080	0.083	0.083	0.083	0.083	0.083	0.083	0.083	0.083	0.083	0.083	0.083
SE															

CORRELATION AND REGRESSION ANALYSES															
Disc Height	Correlation coefficient (r)	Significance	Value	SE _r	Equation	SE _b	SE _a	SE _c	SE _d	SE _e	SE _f	SE _g	SE _h	SE _i	SE _j
Ground	0.618	0.297	16	0.315	0.298	16	0.315	0.298	16	0.315	0.298	16	0.315	0.298	16
Stem Height	0.330	0.357	16	0.316	0.359	16	0.316	0.359	16	0.316	0.359	16	0.316	0.359	16
10 per cent	0.703	0.261	16	0.320	0.214	16	0.320	0.214	16	0.320	0.214	16	0.320	0.214	16
20 per cent	0.853	0.194	16	0.322	0.183	16	0.322	0.183	16	0.322	0.183	16	0.322	0.183	16
30 per cent	0.753	0.249	16	0.320	0.228	16	0.320	0.228	16	0.320	0.228	16	0.320	0.228	16
40 per cent	0.895	0.168	16	0.320	0.177	16	0.320	0.177	16	0.320	0.177	16	0.320	0.177	16
50 per cent	0.899	0.170	16	0.320	0.177	16	0.320	0.177	16	0.320	0.177	16	0.320	0.177	16
60 per cent	0.617	0.298	16	0.312	0.299	16	0.312	0.299	16	0.312	0.299	16	0.312	0.299	16
70 per cent	0.633	0.286	16	0.320	0.323	16	0.320	0.323	16	0.320	0.323	16	0.320	0.323	16

REGRESSION ANALYSIS BETWEEN ABY (Y) AND ABY (X)															
Location	SE _b	SE _a	SE _c	SE _d	SE _e	SE _f	SE _g	SE _h	SE _i	SE _j	SE _k	SE _l	SE _m	SE _n	SE _o
1	0.284	0.411	2	0.044	0.075	4.216	0.075	4.216	0.075	4.216	0.075	4.216	0.075	4.216	0.075
2	0.380	0.264	2	0.087	0.113	0.714	0.113	0.714	0.113	0.714	0.113	0.714	0.113	0.714	0.113
3	0.118	0.875	2	0.010	0.031	14.463	0.031	14.463	0.031	14.463	0.031	14.463	0.031	14.463	0.031
4	0.118	0.794	2	0.009	0.032	20.855	0.032	20.855	0.032	20.855	0.032	20.855	0.032	20.855	0.032
5	0.266	0.472	2	0.010	0.051	12.775	0.051	12.775	0.051	12.775	0.051	12.775	0.051	12.775	0.051
6	0.183	0.774	2	0.008	0.059	24.411	0.059	24.411	0.059	24.411	0.059	24.411	0.059	24.411	0.059
7	0.325	0.354	2	0.013	0.054	6.166	0.054	6.166	0.054	6.166	0.054	6.166	0.054	6.166	0.054
8	0.254	0.499	2	0.014	0.085	4.862	0.085	4.862	0.085	4.862	0.085	4.862	0.085	4.862	0.085
9	0.234	0.520	2	0.015	0.122	2.509	0.122	2.509	0.122	2.509	0.122	2.509	0.122	2.509	0.122

ABY = Arithmetic disk value
 ABY = Weighted disk value
 ABY = Arithmetic whole tree value
 ABY = Weighted whole tree value
 n = 2.503, p = 5.26, p = 0.666; significant at five per cent probability level
 n = 3.499, p = 12.35, p = 0.706; significant at one per cent probability level
 n = 5.466, p = 25.35, p = 0.986; significant at 0.1 per cent probability level
 SD = standard deviation
 SE = not significant
 Number of degrees of freedom for statistical tests = 7
 SE = standard error of whole tree values
 SE_b = standard error of the estimate of correlation coefficient
 SE_a = standard error of estimate of regression
 SE_c = standard error of regression coefficient
 SE_d = standard error of regression line given first significance of the regression coefficient given second
 SE_e = variance ratio
 SE = critical values of Student's t distribution

As wood density, is strongly associated with two of the four components of wood variation in this species and is easily and reliably estimated from a single bark to pith sample removed at ten per cent of the tree height, it is an excellent criterion for selection of individual trees for desirable wood properties.

The first section of the work dealing with wood in mature plantation trees is now complete. Only the wood density parameter has been found to adequately describe the variation found in the wood of *E. deglupta* while, at the same time, being available from a single representative sample and requiring only simple procedures for measurement such as the maximum moisture content method (Chapter 5).

The work now considers aspects of phenotypic variability of wood density in the field and genotypic and phenotypic variability in controlled environments to determine if the character is sufficiently heritable to enable its use in a tree improvement programme. To establish whether the work already presented is applicable over the whole geographic range of *E. deglupta*, some provenances have been investigated in Chapter 9. Environmental variation is considered in Chapter 10 and genotypic aspects are investigated in Chapter 11. The observed variation in wood density has been compared with morphological and growth parameters, then partitioned into environmental and genetic components.

Before proceeding with this presentation, some general aspects of the experimental work in controlled environments are discussed (Chapter 8).

CHAPTER 8

EXPERIMENTAL METHODS FOR GROWING PLANTS IN CONTROLLED ENVIRONMENTS

8.1 INTRODUCTION

The following two Chapters describe research carried out under controlled environment conditions in the C.S.I.R.O. "CERES" phytotron (Morse and Evans, 1962). The experimental methods and techniques used will be discussed here as these are common to more than one experiment. Results are presented in Chapters 9 and 10.

Firstly, geographic variation was investigated by using seedlings, of undetermined genetic origin, from several localities over the natural range of *Eucalyptus deglupta*.

Secondly, half-sib seedlings and clonal cuttings of *E. deglupta* were used to separate the observed variation between plants into genetic and environmental components. Most research conducted in controlled environments, on forest tree species, has been based on material of undefined genetic origin. Controlled environment facilities, using suitable genetic material, enable studies of genotypic variation and genotype x environment interactions with minimum replication.

Factors of the environment which affect growth of *E. deglupta* seedlings include extreme and average temperatures in air and growing medium, rainfall, humidity, evaporation, wind, light intensity and wavelength, soil moisture and nutrients, fire, flooding, pathogens and competition between plants.

A detailed study of some of these factors was considered preferable to a superficial examination of all of them. The technique was to allow only one or two factors to vary while attempting to keep the others constant.

Plants were grown in naturally lit glasshouses and "C"-type cabinets (with shutters to control photoperiod).

8.2 PREPARATION OF SEEDLINGS

All seed was stored at about 4°C in plastic containers and fumigated with methyl bromide on entry into the phytotron. The seed was broadcast sown in pots of vermiculite and covered to a depth of about 2 mm with the same material. The pots were placed in a glasshouse at a temperature of 24/19°C*. The pots stood in dishes of water in full light.

After three to four weeks, the seedlings, with one or two pairs of leaves, were pricked out into 13 cm diameter plastic pots filled with vermiculite; two or three per pot.

Plants destined for each treatment were assigned to temperatures in stages as transplanted seedlings died if placed in the higher temperature regimes immediately. Normally, groups were placed in 21/16, 24/19, 27/22°C regimes immediately. Those destined for the 30/24 and 33/28°C glasshouses were placed firstly in 27/22°C for three days, then into the two higher temperature environments at three-day intervals. The experiment commenced when the 33/28°C environment was occupied.

*This convention will be retained throughout. The day (higher) temperature is held from 8.30 a.m. to 4.30 p.m., the night temperature for the remaining 16 hours.

One week after commencement, the plants were reduced subjectively to one per pot while attempting to provide as much uniformity as possible between replicates of the provenance, clone or half-sib family environment cell.

8.3 PREPARATION OF CUTTINGS

The leaves of *E. deglupta* are opposite for some years so nodes in the ortets considered for cloning were distinct. The vegetative propagules used were single nodes consisting of a leaf pair and about 5 mm of the node above and all of the internode stem below the leaf pair (except for the portion assigned to the previous propagule) (Figure 8.1).

Some 75 per cent of the area of each leaf was removed by a transverse cut.

The basal end of each propagule was dipped into water and then into a commercial hormone rooting powder ('Seradix', grade A for hardwoods, May and Baker Ltd., England), the active constituent being indolebutyric acid.

The propagules were then pushed into vermiculite in peat pots almost to the level of the leaf pair.

The pots with propagules were enclosed in a clear plastic tent and submitted to a mist spray with water for a few seconds every four minutes. Temperature was maintained at 24/19°C. Humidity within the tent was close to 100 per cent and the photoperiod was extended to 16 hours with artificial light from incandescent bulbs.

Roots appeared within nine days, and many roots grew through the peat pots within two weeks at which time the axillary buds began to shoot and many of the former leaves were dropped. At this stage, some liquid complete fertilizer was added to the

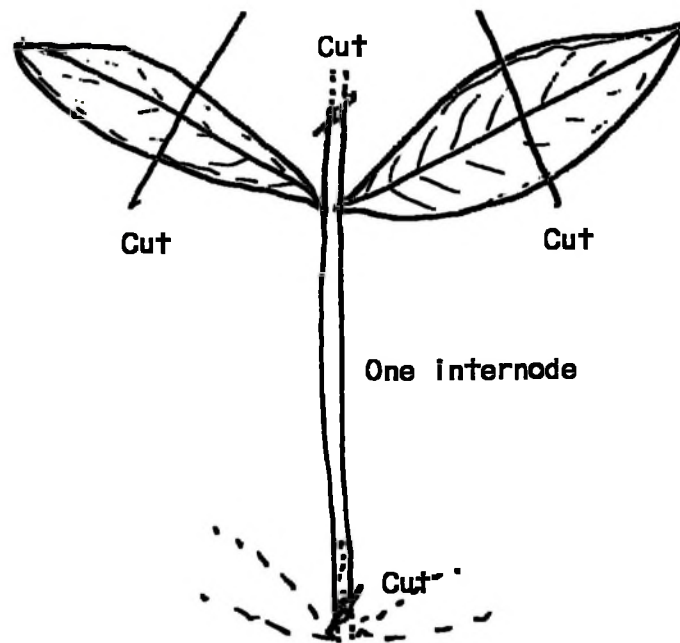


FIGURE 8.1 The preparation of a single stem cutting of *E. deglupta*.

growing medium and the intermittent spray operated at less frequent intervals. Approximately 95-100 per cent rooting success was achieved with *E. deglupta*.

After three weeks, the ramets were transferred to 13 cm diameter plastic pots of vermiculite, three per pot. Some mortality normally occurred at this stage and this was allowed for by growing excess ramets. The ramets were kept temporarily at 24/19°C.

Apical dominance of the shoots was established early. The plants were reduced to one ramet per pot and one shoot per node (often both axillary buds develop together). When it was apparent that the plants were established and healthy (about four weeks after preparation of the cuttings) they were transferred to the experimental treatments.

8.4 ARRANGEMENT OF EXPERIMENTS

Experiments in restricted spaces in glasshouses and cabinets are liable to numerous sources of error. Elaborate methods may be required to avoid or reduce many of them, but great gains in precision may be achieved by attention to the design and layout of the experiment, so that their effects are either measured as 'error' or distributed as evenly as possible between replicates of treatments.

Frequent re-arrangement of plants in new relative positions has been adopted in certain instances by many workers. The method of re-arrangement shares any inequalities of environment between plants, provided these inequalities do not vary relatively if the environment changes.

Frequent re-arrangement does not allow any quantitative measure of the precision and error of the experimental data or the

estimation of their significance (the probability that they are real and valid and not coincidental or due to unsuspected environmental, biotic or other external influence). This precision can only be obtained by use of a statistical procedure applied to the layout. The layout can be designed to eliminate or balance error and to extract the maximum amount of required information.

The method adopted here combined frequent re-arrangement with randomization. The randomization satisfied the statistical criteria and re-arrangement ensured that environmental effects were evenly distributed.

(a) Glasshouses

The layout of the experiment took into account the characteristics of the glasshouse space. These included width, number and direction of benches, likelihood of draught, distribution of ventilators, heating units and light and shade.

All plants were grown on top of the heat-pumps (see Morse and Evans, 1962). All plants in each treatment were grown in the one restricted area of the glasshouse to minimize effects of within-glasshouse differences. To control possible differences in watering and fertilizing, pots were stood in large trays 34 x 32 inches (81 x 86 cms) of dilute Hoagland solution 2-4 cms deep. Roots grew through holes in the bottom of the pots into the solution thus reducing differential water or nutrient stresses.

The plants were randomized at the beginning of the experiment. The trays were rotated through 90° each week and plants were randomized again every four weeks.

Glasshouse temperatures used were 21/16, 24/19, 27/22, 30/25 and 33/28°C.

Mean temperatures throughout the area of the heat pump benches were within $\pm 1.5^{\circ}\text{C}$ of the specified glasshouse temperature. Relative humidity was not controlled but remained above 40 per cent in all glasshouses.

Incandescent lamps above the benches provided illumination of about 25 foot candles at plant height to extend the daylength in all glasshouses to 16 hours (4.00 a.m. to 8.00 p.m.) throughout the experiments.

Plants were watered with tap-water in the morning and standard Hoaglands solution in the afternoon.

(b) C-type cabinets

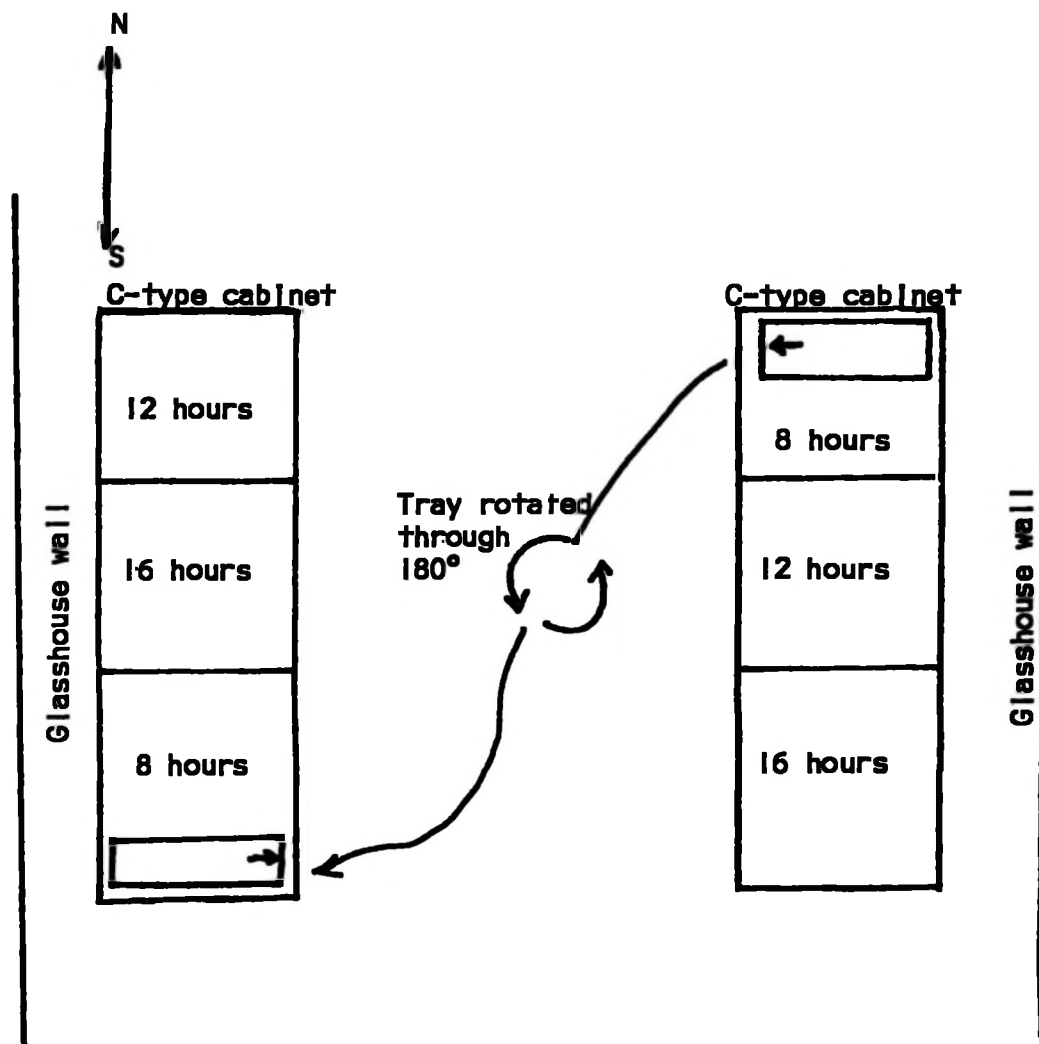
These cabinets are divided into three sections each holding up to 24 thirteen centimetre diameter pots in two trays.

In summer, the light intensity in these naturally lit cabinets is closely comparable but in winter, in the triple C units, there may be a gradient of decreasing light intensity from north to south on clear days. C-cabinets were selected in comparable locations in different glasshouses and by using two triple cabinets opposite each other in the same glasshouse with a different arrangement of treatments (Figure 8.2) the gradient was minimized.

The pots in each tray were assigned randomly at the beginning of the experiment. Each week an operation similar to the one in Figure 8.2 was carried out. Every four weeks the treatment was randomized again.

Mean air temperatures in the cabinets were controlled to within $\pm 0.25^{\circ}\text{C}$ by day. The cabinets were operated on a constant day/night temperature alteration of 24/19, 27/22 and 33/28 $^{\circ}\text{C}$.

FIGURE 8.2 Diagrammatic representation of layout in glasshouse when using C-type cabinets.



Trays, each holding 24 plants, are regularly moved from a cabinet on one side of the glasshouse to the same regime in the cabinet on the other. The regimes are set in a different order in each cabinet to minimize effects of varying light intensity, especially North-South during winter.

The natural daylight period was limited to eight hours by automatic light-proof shutters. Photoperiod extensions to 12 and 16 hours were provided by incandescent lamps, giving intensities of at least 25 foot candles at plant height.

The time control settings for temperature, daylight and photoperiod light cycles were accurate to about ± 3 minutes.

Plants were watered with tap-water in the morning and a standard Hoagland's solution in the afternoon. In the 33/28°C temperature additional water was applied at mid-day.

8.5 MEASUREMENT OF RESPONSES

The primary interest was the density of stem wood produced but as this was probably affected by seedling growth rate and size, seedling growth parameters were also measured.

(a) Measurements on plants during treatments

It was hoped to study the time course of growth responses to environmental variables as well as the final effect judged at harvest. This necessitated a series of measurements at frequent, regular intervals.

In this study the sampling methods were required to be non-destructive, so parameters such as leaf area, leaf dimensions, diameter and height of stem, number of stem internodes, number of leaf pairs and so on were used to characterize individual plants.

Plants were allowed to grow for 55 to 60 days, depending on the particular experiment. At the end of this period, the node just forming was marked with cotton and paper tag (week 0). Measurements were then made each week for the following four

(weeks 1-4) or five weeks (weeks 1-5) at the end of which the plants were harvested for weight measurements. The reader should refer to Figure 8.3 during the following explanation.

I. Height

The distance from the top edge of the pot to the tagged node was measured to the nearest millimetre, at week 0 and each subsequent week. At week 0 this represented total height. For subsequent weeks plant height was obtained from the height to tagged node plus the sum of the internode lengths above the tag.

II. Internode length

Each week the lengths of internodes above the tag were measured to the nearest millimetre. Up to five nodes formed after tagging were measured separately. Thereafter only the number of additional nodes and their sum length were measured.

III. Stem diameter

Each week the basal diameter of the stem between the lowest distinguishable nodes was measured to the nearest 0.1 millimetre.

IV. Number of Internodes

At week 0, the number of internodes up to the tag was counted. At subsequent measures only the number of internodes above the tag was counted and added to this original value.

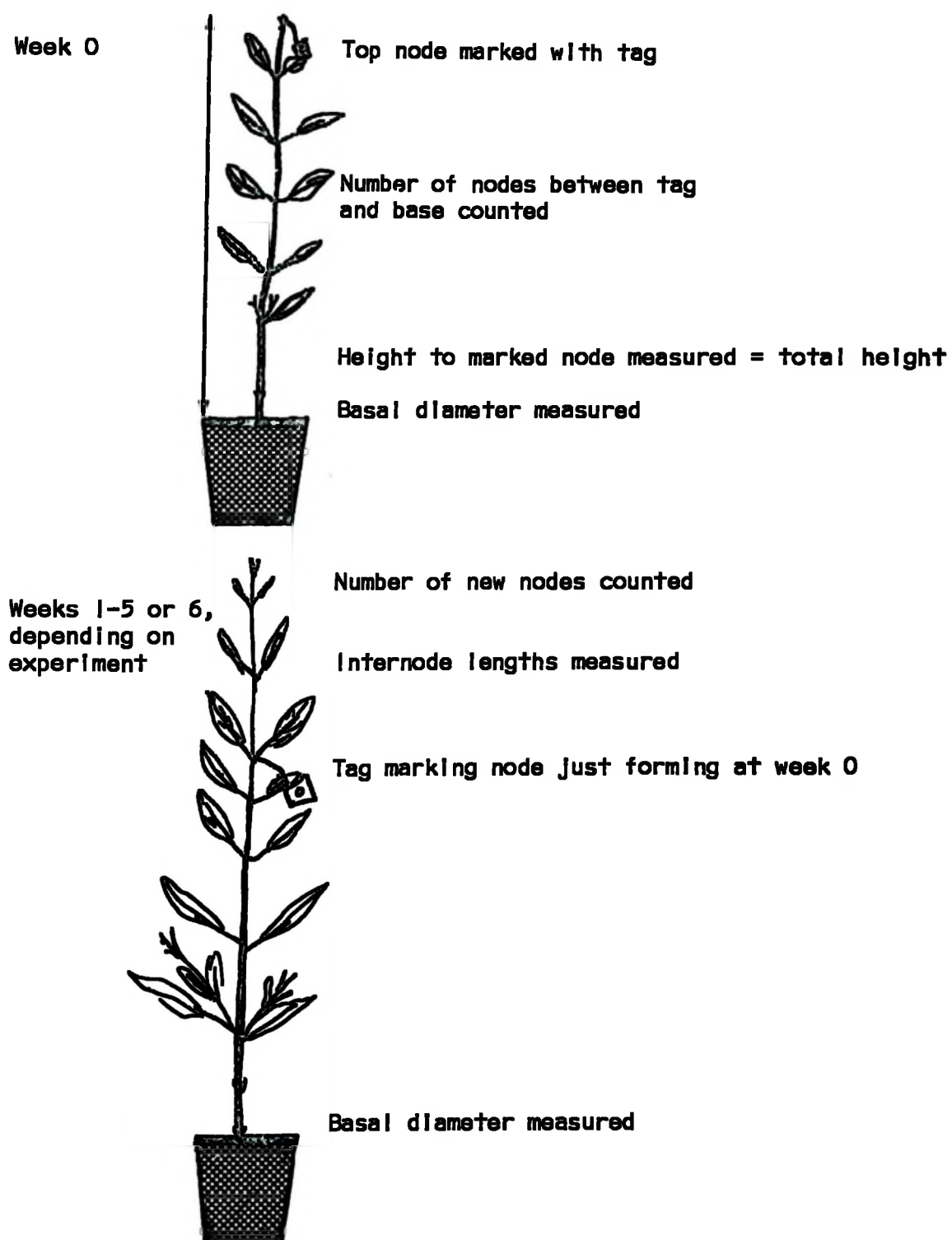


FIGURE 8.3 Plant measurement (for explanation, see text on page 165).

(b) Measurements on harvested plants

1. Relative growth rate

The size of a plant at the end of the experiment depends on both initial size and absolute growth rate during the experimental period. To remove the effects of any initial size differences between treatments relative growth rates (Blackman, 1919; Fisher, 1920) may be calculated with reference to some point in time.

Relative growth rate (R) for any parameter (P) may be expressed by

$$R_P = \frac{1}{P} \cdot \frac{dP}{dt}$$

or

$$R_P = \frac{\log_e (P_2/P_1)}{t_2 - t_1} \quad (8.1)$$

where P_1 and P_2 are measurements of the parameter at times t_1 and t_2 ,

Relative rates were determined for height growth, stem diameter growth and internode initiation using the marked node as the reference point in time (t_1).

11. Assimilation rate

Relative growth rate of plant dry weight has been analysed by Williams (1946) and Evans and Hughes (1961) and found to be the product of leafiness and photosynthetic efficiency of the leaves.

$$R_W = EF$$

where R_W = relative growth rate expressed as plant dry weight

E = leafiness

F = photosynthetic efficiency

The leafiness (F) was measured as a ratio of leaf area to plant dry weight

$$F = A/W$$

where A = leaf area

W = plant dry weight

The photosynthetic efficiency was measured as net assimilation rate (E)

$$E = \frac{1}{A} \cdot \frac{dW}{dt}$$

where A = leaf area

W = plant dry weight

To use these formulae, plant dry weight would need to be calculated at two points in time. This procedure would require growing pairs of plants, one being harvested at time t_1 and the other at time t_2 . There would always be doubt that the two plants were similar. In this study a crude attempt was made to estimate assimilation rate without destructive sampling by taking the two leaves which originated at the marked node and measuring their area and dry weight and expressing the ratio of these on a rate of growth per week basis. This was termed leaf assimilation rate (LAR).

$$LAR = \frac{1}{t} \cdot \frac{W}{A} \quad (8.2)$$

where W = mean leaf weight

A = mean leaf area

iii. Weights of stem parts at harvest

Oven dry weights were determined for the main stem, branches and leaves of each plant. The roots were not harvested. The drying time was about five days at 80°C.

iv. Number of leaf pairs

These were determined by counting at harvest time.

v. Number of branches

This was also determined by counting at harvest time.

vi. Leaf length and width

At harvest time, length and width of the two leaves which originated at the marked node were measured. Width was taken at the widest part of the leaf along a line intersecting the mid-rib at right angles. Length was taken along the mid-rib from the leaf tip to the base, excluding the short petiole.

vii. Wood density

Sample representativeness is important when considering wood density in young seedlings grown under controlled environment

conditions. There is, to the author's knowledge, only one guiding study in the literature. Saucier and Taras (1966) examined seven sprouts from each of two clones of *Acer rubrum* growing close to each other, density being estimated for samples from the middle of the internodes. Analyses indicated density did not differ significantly with height except in the internodes close to the apex.

Sixteen seedlings of undefined genetic origin, of Keravat provenance, were grown in the phytotron for 120 days. Eight were in a glasshouse maintained at 24/19°C and eight in another glasshouse at 27/22°C.

Small, axial stem sections, each approximately two centimetres long, were removed from 10, 20, 30, 40, 50, 60, and 70 per cent of final seedling height. Density of these was determined by the maximum moisture content method (Chapter 5). Weighted tree density averages were derived as previously described using stem diameter as the weighting factor. Results are presented in Table 8.1. These results show that density values, at all height levels investigated, are highly significantly correlated with the whole stem values ($r > 0.742$, significant at 0.1 per cent probability level). However, the standard errors of the estimates of linear regression are lower in the 10 - 40 per cent than in the 50 - 70 per cent height levels. This indicates that sampling at the former heights gives slightly better representations of whole tree values.

TABLE 8.1 CORRELATION AND REGRESSION ANALYSES FOR THE RELATIONSHIP BETWEEN WOOD DENSITY AT SEVEN HEIGHTS IN THE STEM AND WEIGHTED WHOLE STEM DENSITY FOR SIXTEEN SEEDLINGS

OBSERVATION MATRIX

Seedling Number	10 per cent	20 per cent	30 per cent	40 per cent	50 per cent	60 per cent	70 per cent	Weighted Whole Stem Values
1	0.512	0.543	0.504	0.506	0.619	0.557	0.553	0.536
2	0.432	0.421	0.439	0.451	0.414	0.511	0.550	0.447
3	0.544	0.484	0.479	0.474	0.359	0.397	0.452	0.481
4	0.501	0.496	0.481	0.443	0.398	0.387	0.406	0.470
5	0.503	0.544	0.477	0.521	0.443	0.461	0.478	0.499
6	0.523	0.529	0.514	0.444	0.439	0.459	0.474	0.491
7	0.509	0.534	0.521	0.486	0.486	0.384	0.404	0.495
8	0.491	0.486	0.506	0.451	0.431	0.491	0.395	0.477
9	0.481	0.464	0.402	0.397	0.413	0.432	0.414	0.442
10	0.437	0.413	0.340	0.280	0.270	0.280	0.280	0.362
11	0.420	0.400	0.390	0.390	0.380	0.340	0.320	0.389
12	0.401	0.409	0.456	0.428	0.386	0.428	0.363	0.411
13	0.413	0.379	0.419	0.397	0.438	0.404	0.363	0.406
14	0.460	0.509	0.452	0.458	0.421	0.399	0.392	0.449
15	0.374	0.379	0.404	0.391	0.348	0.303	0.317	0.369
16	0.516	0.456	0.466	0.493	0.489	0.443	0.371	0.474
Mean	0.470	0.465	0.453	0.438	0.421	0.417	0.408	0.450
SD	0.051	0.059	0.051	0.059	0.075	0.073	0.078	0.050

CORRELATION AND REGRESSION ANALYSES

Sample Height	Correlation with Whole Stem Mean			Regression with Whole Stem Mean					
	Value	S.E. ₁	Significance	Equation	S.E. ₂	S.E. ₃	Variance Ratio	Significance ₁	Significance ₂
10 per cent	0.855	0.138	***	$Y = 0.053 + 0.845 X$	0.007	0.037	38.201	***	***
20 per cent	0.893	0.120	***	$Y = 0.095 + 0.763 X$	0.006	0.027	55.142	***	***
30 per cent	0.881	0.127	***	$Y = 0.058 + 0.866 X$	0.007	0.033	48.361	***	***
40 per cent	0.865	0.134	***	$Y = 0.127 + 0.738 X$	0.007	0.031	24.120	***	***
50 per cent	0.773	0.169	***	$Y = 0.233 + 0.516 X$	0.009	0.030	20.816	***	***
60 per cent	0.761	0.173	***	$Y = 0.231 + 0.526 X$	0.009	0.032	19.313	***	***
70 per cent	0.784	0.166	***	$Y = 0.244 + 0.506 X$	0.009	0.029	22.335	***	***

Critical values for levels of significance

* $t = 2.145$; $F = 4.60$; $r = 0.497$; significant at the five per cent probability level

** $t = 2.977$; $F = 8.86$; $r = 0.623$; significant at the one per cent probability level

*** $t = 4.140$; $F = 17.14$; $r = 0.742$; significant at the 0.1 per cent probability level

SE_1 = standard error of the correlation coefficient

SE_2 = standard error of the estimate of regression

SE_3 = standard error of the regression coefficient

SD = standard deviation

†Significance of regression line given first; significance of the regression coefficient given second

8.6 ANALYSES OF VARIANCE

The generalized models of the complete analyses of variance in the controlled environment studies are given in Tables 8.2 and 8.3. Different components of these analyses are used later to estimate environmental treatment effects reported in Chapters 9 and 10 and to compute heritability values in Chapter 11.

TABLE 8.2 MODEL OF THE ANALYSIS OF VARIANCE FOR PLANTS GROWN IN PHYTOTRON GLASSHOUSE ENVIRONMENTS

Source	Sum Squares	Degrees of Freedom	Expected Mean Squares
Temperatures RT	$\sum_{i=1}^{RT} (x_{i...} - \bar{x}_{...})^2$	$(RT - 1)$	$\sigma^2 + \frac{RT\sigma^2}{RTNS} + \frac{NS\sigma^2}{RTNR} + \frac{NSNR\sigma^2}{RT}$
Plants NS	$\sum_{j=1}^{NS} (x_{.j.} - \bar{x}_{.j.})^2$	$(NS - 1)$	$\sigma^2 + \frac{RT\sigma^2}{RTNS} + \frac{RT\sigma^2}{RTNS} + \frac{NRRT\sigma^2}{NS}$
Replications NR	$\sum_{k=1}^{NR} (x_{..k} - \bar{x}_{..k})^2$	$(NR - 1)$	$\sigma^2 + \frac{NS\sigma^2}{NRRT} + \frac{RT\sigma^2}{NRNS} + \frac{RTNS\sigma^2}{NR}$
$NS \times RT$	$\sum_{i=1}^{RT} \sum_{j=1}^{NS} (x_{ij.} - \bar{x}_{i..} - \bar{x}_{.j.} + \bar{x}_{...})^2$	$(RT - 1)(NS - 1)$	$\sigma^2 + \frac{RT\sigma^2}{RTNS}$
$NR \times NS$	$\sum_{j=1}^{NS} \sum_{k=1}^{NR} (x_{.jk} - \bar{x}_{.j.} - \bar{x}_{..k} + \bar{x}_{...})^2$	$(NR - 1)(NS - 1)$	$\sigma^2 + \frac{RT\sigma^2}{RTNS}$
$NR \times RT$	$\sum_{i=1}^{RT} \sum_{k=1}^{NR} (x_{i.k} - \bar{x}_{i..} - \bar{x}_{..k} + \bar{x}_{...})^2$	$(NR - 1)(RT - 1)$	$\sigma^2 + \frac{NS\sigma^2}{NRRT}$
$NR \times NS \times RT$	$\sum_{i=1}^{RT} \sum_{j=1}^{NS} \sum_{k=1}^{NR} (x_{ijk} - \bar{x}_{i..} - \bar{x}_{.j.} - \bar{x}_{..k} + \bar{x}_{...})^2$	$(NR - 1)(NS - 1)(RT - 1)$	σ^2
Total ($NRNSRT$)	$\sum_{i=1}^{RT} \sum_{j=1}^{NS} \sum_{k=1}^{NR} (x_{ijk} - \bar{x}_{...})^2$	$(NRNSRT - 1)$	

 RT = number of temperature regimes, $i = 1, \dots, RT$ NS = number of clones or half-siblings, $j = 1, \dots, NS$ NR = number of replications of clones or half-siblings, $k = 1, \dots, NR$

CHAPTER 9

VARIATION WITHIN AND BETWEEN PROVENANCES

9.1 INTRODUCTION

One of the major factors affecting establishment and productivity of plantations is seed origin. Provenance research normally aims at defining the genetic and environmental components of variability between trees of the same species from differing geographic origins to provide a sound basis for selection of seed sources.

The variation in wood properties reported in previous chapters was based on sample material selected from a population of *E. deglupta* plantation trees at Keravat, New Britain. A provenance study has been undertaken to ascertain whether the Keravat population is representative of populations of the species throughout its natural range. The results of provenance studies using seedlings in controlled environments are presented here. Field trials have also been established but results from these are not presently available.

9.2 PRELIMINARY SURVEY

Some information concerning *E. deglupta* distribution has already been presented in Chapter 2. The geographic range has been carefully defined with particular regard to extreme limits in latitude, longitude and altitude. This was achieved by personal visits to many areas by the author, consultations with experienced persons

who have visited many locations, and by examination of herbarium specimens.

An inspection of fresh and dried specimens reveals considerable consistent phenotypic differences between specimens from different regions. The phenotypic differences are reflected particularly in leaf shape and size of inflorescence (Plate 9.1, Figure 9.1).

This morphological evidence has been strengthened by a preliminary assessment of progeny raised from seed obtained at Ossima, New Guinea, and Keravat, New Britain (L.D. Pryor, 1971, personal communication). The leaf shape of progeny show similar differences to those in the adult source (Plate 9.2).

This evidence suggested that a substantial provenance study would be valuable for *E. deglupta*.

9.3 PLANNING

To account for as much variability as possible, extremes of the natural range were sampled. For the phytotron studies, seed was collected from trees in two areas in Mindanao, one in New Britain, one in lowland Papua and one in highland New Guinea. Descriptions of these areas are given in Table 9.1 and locations are marked on the distribution map in Chapter 2 (Figure 2.1). Difficulty in synchronizing seed collecting expeditions with time of seed maturity resulted in from 4 to 25 trees being included in the provenance collections.

TABLE 9.1 PROVENANCE DESCRIPTIONS FOR *E. DEGLUPTA* SEED USED IN
PHYTOTRON STUDIES

Provenance letter designation	Seed lot number	Description
F	S9408	Milibuk area, Cotabato province, Mindanao, Philippines. Near kilometer post 23 of Kraan main line (a major logging road). Weyerhaeuser Philippines Inc. concession area, Palimbang. Latitude: 6°15'N, Longitude: 124°18'E. Elevation: 1300 ft (390 m). The soils were shallow sands to sandy loams, over boulders in the creeks and fractured rocks on the slopes. The trees were located in small groups of many age classes along rocky creeks and land slide faces on steep to very steep slopes. Stand height was about 100 ft (30 m), diameter breast height over bark about 18 in (46 cms). Number of trees in collection = 4. Stem form was variable; buttressing moderate to heavy. Collected 1-15/8/69.
G	S9379	Keravat, New Britain, P.N.G. Latitude: 4°19'S, Longitude: 152°32'E. Elevation: 0-300 m. Soils were alluvial on a river flat. Trees occurred in stands of several even-aged classes. Height of trees 100-130 ft, form good, some buttressing. Number of trees in collection = 25.
I	S8863	Raba Raba, P.N.G. Latitude: 9°58'S, Longitude: 149°50'E. Elevation: 500 ft (150 m). Soils were alluvial sand to silty-sand. Number of trees in collection unknown.
J	HQ335	Kundlawa, New Guinea, P.N.G. Approximate latitude: 6°S, approximate longitude: 145°E. Approximate altitude 6,000 ft (1800 m). Number of trees in collection = 10.
K	S9291	Callwan River, Davao del Norte province, Mindanao. 2 km north to 1 km east of Extensive Enterprises Inc. Camp. Latitude: 7°36'N, Longitude: 126°07'E, Altitude 1700-1720 ft (510 m). Soils were shallow, sand to silty-sand. Area was a small, extremely rocky, alluvial fan, dissected by river channels. Slope: 5-15°. Aspect: northerly. Stand height was 160-190 ft (48-57 m) and tree diameters 21-41 inches (53.3-103.9 cms). Trees of good form, slight-moderate buttressing. Number of trees in collection = 8.

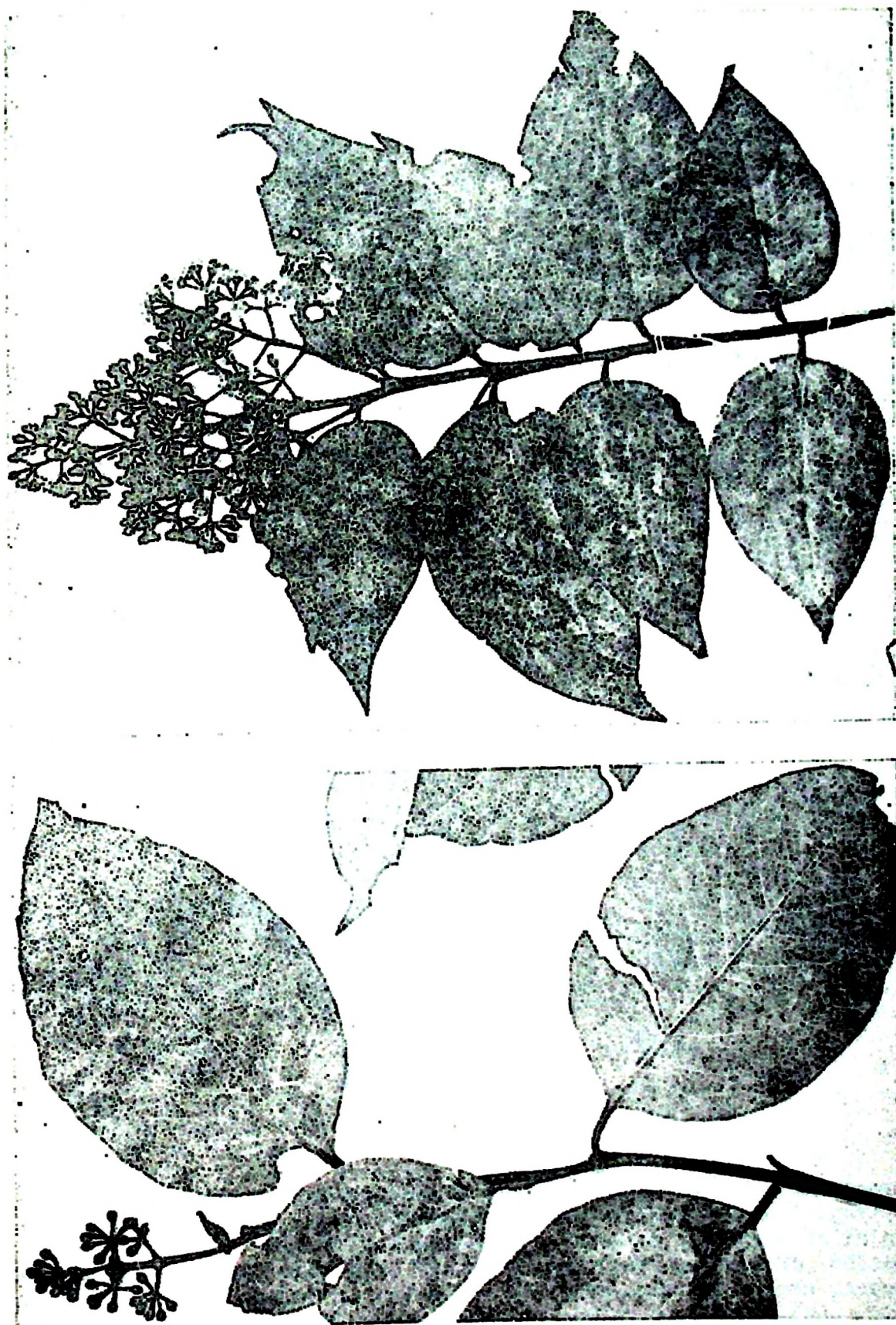


PLATE 9.1 The adult specimen on the left is from Ossima, New Guinea. It is characterized by rounded leaves. In contrast, the New Britain material (right) has longer leaves, with pronounced elongate tips.

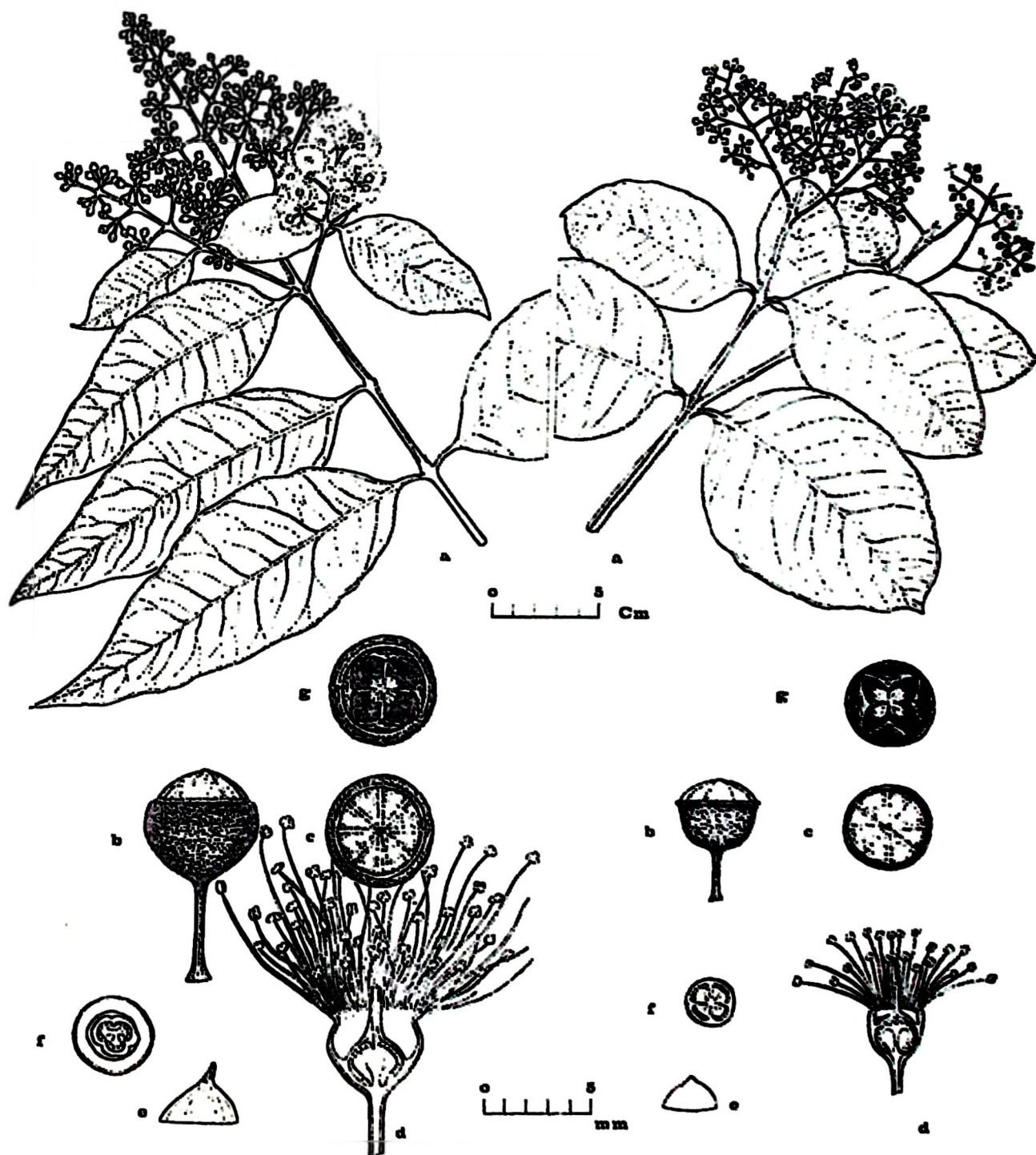


FIGURE 9.1 Comparative diagrams of the morphology of two provenances, one from New Britain (left) and one from Garaina, New Guinea (right). The illustrations show the marked variability which can occur in this species. (Diagram drawn by N. Howcroft, Department of Forests, Bulolo.) a, shape and arrangement of leaves and inflorescence; b, green capsule; c, green capsule; d, median longitudinal section of flower; e, operculum; f, transverse section of ovary; g, open capsule.



PLATE 9.2 Seedlings grown from seed of two different provenances. One parent had broad leaves without pronounced tips. This feature is reflected in the progeny on the left. The other parent had leaves with pronounced drip-tips. The progeny on the right also exhibits this character. (Author's photographs of specimens grown in the Botany Department, A.N.U., and loaned by Professor L.D. Pryor).

9.4 PRELIMINARY EXPERIMENTATION

Eight seedlings from each of the five provenances were grown in C-type phytotron cabinets for 108 days at 27/22°C and 12 hour daylength (Chapter 8). Measurements were made in each of the final five weeks and at harvesting. The results were investigated using principle component and factor analyses to determine the main components of variation between provenances grown at a controlled temperature and daylength.

The designations for variables are given in Table 9.2, correlations between variables in Table 9.3. Density of the Internode above the marked node ($x_{29}(DENSN)$) is correlated at the five per cent level with basal stem density ($x_{31}(DENSB)$); at the one per cent level with basal stem diameter ($x_{30}(DIAMB)$), branch weight ($x_{34}(BRWT)$) and rate of basal stem diameter growth ($x_{11}(RTDIA)$), and at the 0.1 per cent level with total stem oven dry weight ($x_{36}(STWT)$).

Density of the basal stem Internode ($x_{31}(DENSB)$) is correlated at the five per cent level with density of the node above the marked node ($x_{29}(DENSN)$), rate of height growth ($x_{33}(RTHT)$), and unit leaf weight ($x_{35}(LEAF)$); at the one per cent level with rate of basal stem diameter growth and at the 0.1 per cent level with branch oven dry weight ($x_{34}(BRWT)$), stem oven dry weight ($x_{36}(STWT)$) and total final height ($x_{42}(TOTHT)$).

To determine which of these indicated associations are real, principal component and factor analyses were carried out on the correlation matrix (Tables 9.4 and 9.5).

TABLE 9.2 LIST OF VARIABLES MEASURED IN PRELIMINARY PROVENANCE
EXPERIMENT

28. Total number of nodes produced (*TNODES*)
29. Density of stem wood in the internode above the marked node (*DENSEN*) (gms/cc)
30. Basal stem diameter underbark at harvest (*DIAMB*) (cm)
31. Density of the wood at the base of the stem (*DENSEB*) (gms/cc)
32. Rate of elongation of the internode above the marked node (i.e., where the density sample in 29 was obtained) (*RELONG*) (cms/week)
33. Rate of total height growth (*RTHH*) (cms/week)
34. Branch oven dry weight at harvest (*BRWT*) (gms)
35. Mean oven dry weight of the two leaves at the marked node at harvest (*LEAF*) (gms)
36. Stem oven dry weight at harvest (*STWT*) (gms)
37. Mean leaf area of the two leaves at the marked node at harvest (*AREA*) (sq inches)
38. Mean leaf width of the two leaves at the marked node at harvest (*WIDTH*) (cms)
39. Mean leaf length of the two leaves at the marked node at harvest (*LENGTH*) (cms)
40. Rate of diameter growth of the base of the stem (*RTDIA*) (cms/week)
41. Rate of diameter growth of the internode above the marked node (i.e., where the density sample in 29 was obtained) (*RTDIAN*) (cms/week)
42. Total height of plant at time of harvest (*TOTHT*) (cms)

[See Chapter 8 for more detailed descriptions of measured parameters.]

TABLE 9.3 CORRELATION COEFFICIENTS BETWEEN VARIABLES MEASURED ON SEEDLING PROVENANCES GROWN IN A CONTROLLED ENVIRONMENT

	x_{28}	x_{29}	x_{30}	x_{31}	x_{32}	x_{33}	x_{34}	x_{35}	x_{36}	x_{37}	x_{38}	x_{39}	x_{40}	x_{41}	x_{42}
x_{28} (TNODES)	1.00	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS
x_{29} (DENSE)	+0.35	1.00	**	*	NS	NS	**	NS	***	NS	NS	NS	NS	**	NS
x_{30} (DIAMB)	+0.40	+0.61	1.00	NS	NS	*	***	*	***	NS	NS	NS	*	***	***
x_{31} (DENSE)	+0.32	+0.50	+0.82	1.00	NS	*	***	*	***	NS	NS	NS	NS	**	***
x_{32} (RELONG)	+0.26	-0.01	+0.02	+0.02	1.00	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
x_{33} (RETT)	+0.39	+0.00	+0.58	+0.60	+0.14	1.00	NS	*	NS	NS	NS	*	**	*	***
x_{34} (RETT)	+0.45	+0.70	+0.88	+0.77	-0.09	+0.41	1.00	*	***	NS	NS	NS	NS	***	**
x_{35} (LEAF)	+0.28	+0.10	+0.49	+0.60	-0.07	+0.55	+0.38	1.00	NS	***	***	***	NS	*	**
x_{36} (SWT)	+0.46	+0.75	+0.91	+0.79	-0.06	+0.42	+0.91	+0.55	1.00	***	NS	NS	NS	***	***
x_{37} (AREA)	+0.04	-0.21	+0.14	+0.27	-0.02	+0.38	-0.01	+0.87	+0.18	1.00	***	***	NS	NS	NS
x_{38} (WIDTH)	+0.00	-0.20	+0.12	+0.25	-0.03	+0.32	-0.06	+0.86	+0.17	+0.98	1.00	NS	NS	NS	NS
x_{39} (LENGTH)	+0.15	-0.18	+0.21	+0.38	+0.03	+0.51	+0.05	+0.88	+0.24	+0.96	+0.91	1.00	*	NS	NS
x_{40} (RTDIAM)	+0.13	+0.05	+0.60	+0.51	+0.08	+0.64	+0.43	+0.46	+0.45	+0.23	+0.21	+0.29	1.00	***	**
x_{41} (RTDIA)	+0.57	+0.64	+0.84	+0.69	-0.06	+0.55	+0.84	+0.50	+0.85	+0.22	+0.18	+0.31	+0.48	1.00	***
x_{42} (TOTHT)	+0.39	+0.46	+0.84	+0.79	+0.05	+0.75	+0.65	+0.62	+0.81	+0.33	+0.29	+0.45	+0.66	+0.76	1.00

* $r > 0.48$, significant at the five per cent probability level

** $r > 0.61$, significant at the one per cent probability level

*** $r > 0.72$, significant at the 0.1 per cent probability level

NS = not significant at five per cent level

TABLE 9.4 RESULTS OF PRINCIPAL COMPONENTS ANALYSIS ON PARAMETERS
MEASURED ON SEEDLINGS OF DIFFERENT PROVENANCES GROWN
IN A PHYTOTRON CABINET*

Component or eigen vector number	1 (ξ_1)	2 (ξ_2)	3 (ξ_3)	4 (ξ_4)
Eigen values	7.32 λ_1	3.43 λ_2	1.30 λ_3	1.08 λ_4
Cumulative percentage of eigen values	45.7	67.2	75.3	82.0
Percentage of total eigen values in each component	45.7	21.5	8.1	6.7
x_{28} (TNODES)	+0.18	-0.12	<u>+0.29</u>	-0.54
x_{29} (DENSE)	<u>+0.19</u>	-0.35	-0.28	-0.30
x_{30} (DIAMB)	<u>+0.33</u>	-0.18	-0.00	+0.11
x_{31} (DENSE)	<u>+0.32</u>	-0.07	-0.03	+0.09
x_{32} (RELONG)	+0.01	-0.00	<u>+0.69</u>	-0.38
x_{33} (RTHT)	+0.27	+0.10	+0.39	<u>+0.26</u>
x_{34} (BRWT)	<u>+0.30</u>	-0.28	-0.14	0.00
x_{35} (LEAF)	+0.29	+0.30	-0.13	-0.09
x_{36} (STWT)	<u>+0.33</u>	-0.18	-0.18	-0.09
x_{37} (AREA)	+0.17	<u>+0.46</u>	-0.12	-0.14
x_{38} (WIDTH)	+0.16	<u>+0.46</u>	-0.16	-0.14
x_{39} (LENGTH)	+0.21	<u>+0.43</u>	-0.02	-0.12
x_{40} (RTDIA)	+0.23	+0.03	+0.29	<u>+0.54</u>
x_{41} (RTDIAN)	<u>+0.32</u>	-0.14	-0.06	-0.09
x_{42} (TOTHT)	<u>+0.34</u>	-0.03	+0.10	+0.15

The important members of each component are underlined and in bold type. These important variables were ascertained from the size of the correlations in Table 9.5.

*These results are for one photoperiod (12 hour day) within one temperature regime (27/22°C).

TABLE 9.5 ROTATED FACTOR ANALYSIS RESULTS SHOWING CORRELATIONS
BETWEEN VARIABLES AND COMPONENTS

Variables	Factors			
	F_1	F_2	F_3	F_4
x_{28}	+0.52	+0.09	<u>+0.67</u>	-0.03
x_{29}	<u>+0.87</u>	-0.20	+0.03	-0.20
x_{30}	<u>+0.84</u>	+0.09	+0.03	+0.45
x_{31}	<u>+0.73</u>	+0.25	+0.01	+0.43
x_{32}	-0.13	-0.05	<u>+0.86</u>	+0.13
x_{33}	+0.28	+0.32	+0.25	<u>+0.76</u>
x_{34}	<u>+0.92</u>	-0.03	-0.03	+0.24
x_{35}	+0.37	+0.07	-0.00	+0.25
x_{36}	<u>+0.94</u>	+0.17	+0.00	+0.20
x_{37}	-0.01	<u>+0.99</u>	-0.01	+0.10
x_{38}	-0.01	<u>+0.98</u>	-0.05	+0.06
x_{39}	+0.05	<u>+0.95</u>	+0.08	+0.21
x_{40}	+0.25	+0.13	-0.02	<u>+0.87</u>
x_{41}	<u>+0.85</u>	+0.19	+0.10	+0.26
x_{42}	<u>+0.67</u>	+0.29	+0.09	+0.57

The larger correlations (in bold type and underlined) were used subjectively to indicate the important variables in each of the four components of variation in Table 9.4.

The four factors F_{1-4} are related to the four components in Table 9.4. $F_i = \xi_{ij} \cdot \lambda^{-0.5}$

The cumulative percentage of eigen values indicates that 82 per cent of the total variation in the seedlings can be described by four components. The important variables in first component, represent 45.7 per cent of the total variation, are stem and branch weights (x_{36} (*STWT*)) and (x_{34} (*BRWT*)), basal stem diameter (x_{30} (*DIAMB*)), total seedling height (x_{42} (*TOTHT*)), stem density above the marked node (x_{29} (*DENSN*)) and basal stem density (x_{31} (*DENSB*)). As density is a measure of the amount of solid material present per unit volume the association of density with branch and stem weight is to be expected. The important information given by the first component is that the two density values, both of which have been shown to represent whole stem density (Table 8.1), are associated with parameters of seedling size (stem basal diameter (x_{30} (*DIAMB*)) and total height (x_{42} (*TOTHT*)) and rate of diameter growth of the stem internode section from which one of the density samples was removed (x_{41} (*TRDIAN*)).

The second component is associated with leaf size (leaf length (x_{39} (*LENGTH*)), leaf width (x_{38} (*WIDTH*)), leaf area (x_{37} (*AREA*))) and represents 21.5 per cent of the total variability in the seedlings.

The total number of internodes (x_{28} (*TNODES*)) and the rate of elongation of the marked internode (x_{32} (*RELONG*)), appear with relatively large scores in the third component representing only 8.1 per cent of the total variation.

Two variables concerning the rate of seedling growth appear important in the fourth component representing 6.7 per cent of the total variation. These are rate of basal stem diameter growth

(x_{40} (RTDIA)) and rate of seedling height growth (x_{33} (RTHT)).

The correlation and principal components analyses show that density is strongly associated with parameters of seedling size such as seedling height and stem diameter. This interdependence makes difficult interpretation of any analyses of variance made on seedling data. However, an analysis of variance for density is given for the main provenance study in the next section of this chapter. It is hoped to appreciate how wood density varies with provenance, despite its apparent association with aspects of growth.

9.5 PROVENANCE STUDY

The five provenances were grown in C-type phytotron cabinets at three temperature regimes and three daylengths per temperature (Chapter 8). There were eight seedlings of each provenance in each temperature-photoperiod cell.

temperatures	x	photoperiods	x	provenances	x	replicates	=	total seedlings
3		3		5		8	=	360

The plants were grown for 108 days with measurements taken during the last five weeks and at harvest time as described previously (Chapter 8).

The analysis of variance for wood density (Table 9.6) followed the general model given in Table 8.3. The between provenance mean square was tested against an error mean square derived from the sum of all the mean squares containing a replication (RR) component.

**TABLE 9.6 PARTIAL ANALYSIS OF VARIANCE TABLE
FOR WOOD DENSITY IN PROVENANCES**

Source	Degrees of Freedom	Mean Square	Variance Ratio
Provenances	4	0.001313	1.34 NS
Error	315	0.000980	

NS = not significant at the five per cent probability level

9.6 RESULTS AND DISCUSSION

The partial analysis of variance table is presented in Table 9.6. There was no significant difference in wood density shown between provenances in this limited study with only four degrees of freedom for provenances. However, there is an indication that the wood density work can be applied to *E. deglupta* over most of its natural range. As the New Britain Provenance (Keravat material) is likely to be used extensively, the following work will describe growth studies in controlled environments (Chapter 10), heritability (Chapter 11) and tree selection (Chapter 12) dealing with this single provenance.

CHAPTER 10

ENVIRONMENTAL VARIATION IN WOOD DENSITY

10.1 INTRODUCTION

There is little variation in wood density between seedlings of provenances of *E. deglupta*. In this Chapter environmental variation is investigated only to derive components of variance which will be used to estimate heritability in Chapter 11. It is not intended to elucidate matters of physiological importance when *E. deglupta* plants are grown in controlled environments.

A number of previous investigations have been made into the effects of controlled environments on wood density but generally cell diameter and cell wall thickness as components of density have been considered rather than wood density *per se*.

Under conditions of controlled temperature, both light intensity and daylength have been shown to affect wood density of forest tree seedlings (e.g., Dinwoodie and Richardson, 1961; Balatinecz and Farrar, 1968; Waisel and Fahn, 1965). Little work has been carried out on the genus *Eucalyptus*. Decisions concerning methods, sample size and analysis in this present work have largely been based on the work of Higgs (1969) and Eldridge (1969).

10.2 EXPERIMENTAL

Two experiments were carried out to obtain data for the later calculation of broad and narrow sense heritabilities. The material was from the Keravat provenance.

(a) Experiment 1

Ten clones of *E. deglupta*, raised from cuttings, were grown under controlled environments in C-type cabinets. There were three temperature regimes; 21/16°C, 27/22°C and 33/28°C, three daylengths; 8, 12 and 16 hours, with five replications per temperature-daylength cell.

temperatures	x	photoperiods	x	clones	x	replications	=	total plants
3		3		10		5	=	450

Length of experiment was 108 days. Experimental methods and measurement of parameters were discussed in Chapter 8.

(b) Experiment 2

Twenty half-sib* families were grown in the phytotron glasshouses at five temperatures; 21/16°C, 24/19°C, 27/22°C, 30/25°C and 33/28°C. There were five replications per family.

temperatures	x	families	x	replications	=	total seedlings
5		20		5	=	500

Length of this experiment was 128 days.

*Assumed: see later discussion.

10.3 ANALYSES OF VARIANCE

The general models given in Chapter 8 were modified by grouping mean squares to suit the experimental requirements. For example in Experiment 1 the modified model for analysis of variance would be as given in Table 10.1, where those mean squares containing a replication mean square as a component are included in an error term. In this example the between clone mean square would be tested against the error mean square. The significance of the resulting variance ratio (F) was determined by reference to tables such as those in Rohlf and Sokal (1969; pages 168-197). The model of analysis of variance for Experiment 2 is given in Table 10.2.

10.4 RESULTS

The analyses of variance for the two experiments are given in Table 10.3.

In Experiment 1, differences in wood density between clones was significant at the one per cent level. There was a pronounced clone x temperature interaction effect (significant at the five per cent level).

In Experiment 2, there were significant differences in wood density (at the one per cent level of probability) between families. An interaction effect of temperature x family was significant at the five per cent level of probability.

TABLE 10.1 MODEL FOR UNIVARIATE ANALYSIS OF VARIANCE IN EXPERIMENT 1 AND ESTIMATION OF OBSERVATIONAL COMPONENTS OF VARIANCE ASSUMING RANDOM ENVIRONMENTAL AND CLONE EFFECTS

Source	Degrees of Freedom	Mean Squares	Estimated Mean Squares
Temperatures	$(UT - 1)$	MS_U	$\sigma_U^2 + \overline{MRo}_{TPS}^2 + \overline{MRo}_{ST}^2 + \overline{MRo}_{TP}^2 + \overline{MRo}_{SP}^2 + \overline{MRo}_{TS}^2 + \overline{MRo}_{ST}^2 + \overline{MRo}_{TP}^2 + \overline{MRo}_{SP}^2 + \overline{MRo}_{TS}^2$
Photoperiods	$(MP - 1)$	MS_P	$\sigma_P^2 + \overline{MRo}_{TPS}^2 + \overline{MRo}_{ST}^2 + \overline{MRo}_{TP}^2 + \overline{MRo}_{SP}^2 + \overline{MRo}_{TS}^2 + \overline{MRo}_{ST}^2 + \overline{MRo}_{TP}^2 + \overline{MRo}_{SP}^2 + \overline{MRo}_{TS}^2$
Clones	$(MS - 1)$	MS_S	$\sigma_S^2 + \overline{MRo}_{TPS}^2 + \overline{MRo}_{ST}^2 + \overline{MRo}_{TP}^2 + \overline{MRo}_{SP}^2 + \overline{MRo}_{TS}^2 + \overline{MRo}_{ST}^2 + \overline{MRo}_{TP}^2 + \overline{MRo}_{SP}^2 + \overline{MRo}_{TS}^2$
Clones x Temperatures	$(MS - 1)(UT - 1)$	MS_{ST}	$\sigma_{US}^2 + \overline{MRo}_{TPS}^2 + \overline{MRo}_{ST}^2 + \overline{MRo}_{TP}^2 + \overline{MRo}_{SP}^2 + \overline{MRo}_{TS}^2 + \overline{MRo}_{ST}^2 + \overline{MRo}_{TP}^2 + \overline{MRo}_{SP}^2 + \overline{MRo}_{TS}^2$
Clones x Photoperiods	$(MS - 1)(MP - 1)$	MS_{SP}	$\sigma_{PS}^2 + \overline{MRo}_{TPS}^2 + \overline{MRo}_{ST}^2 + \overline{MRo}_{TP}^2 + \overline{MRo}_{SP}^2 + \overline{MRo}_{TS}^2 + \overline{MRo}_{ST}^2 + \overline{MRo}_{TP}^2 + \overline{MRo}_{SP}^2 + \overline{MRo}_{TS}^2$
Temperatures x Photoperiods	$(UP - 1)(UT - 1)$	MS_{TP}	$\sigma_{UP}^2 + \overline{MRo}_{TPS}^2 + \overline{MRo}_{ST}^2 + \overline{MRo}_{TP}^2 + \overline{MRo}_{SP}^2 + \overline{MRo}_{TS}^2 + \overline{MRo}_{ST}^2 + \overline{MRo}_{TP}^2 + \overline{MRo}_{SP}^2 + \overline{MRo}_{TS}^2$
Clones x Photoperiods x Temperatures	$(MP - 1)(MS - 1)(UT - 1)$	MS_{TPS}	$\sigma_{UPS}^2 + \overline{MRo}_{TPS}^2 + \overline{MRo}_{ST}^2 + \overline{MRo}_{TP}^2 + \overline{MRo}_{SP}^2 + \overline{MRo}_{TS}^2 + \overline{MRo}_{ST}^2 + \overline{MRo}_{TP}^2 + \overline{MRo}_{SP}^2 + \overline{MRo}_{TS}^2$
Error	$MPMS(MR - 1)$	MS_U	$\sigma_U^2 + \overline{MRo}_{TPS}^2 + \overline{MRo}_{ST}^2 + \overline{MRo}_{TP}^2 + \overline{MRo}_{SP}^2 + \overline{MRo}_{TS}^2 + \overline{MRo}_{ST}^2 + \overline{MRo}_{TP}^2 + \overline{MRo}_{SP}^2 + \overline{MRo}_{TS}^2$
Total	$(MSMPMUT - 1)$		

The meaning of some abbreviations are given in Table 8.3 which describes the full analysis from which this specific model is derived. The others are:

- MS_U = between temperatures mean square
- MS_P = between photoperiods mean square
- MS_S = between clones mean square
- MS_{ST} = clone x temperature interaction mean square
- MS_{SP} = clone x photoperiod interaction mean square
- MS_{TP} = temperature x photoperiod interaction mean square
- MS_{TPS} = temperature x photoperiod x clone interaction mean square
- MS_U = within clone mean square
- σ_U^2 = within clone variance
- σ_{US}^2 = temperature x photoperiod x clone interaction variance
- σ_{UP}^2 = temperature x photoperiod interaction variance
- σ_{PS}^2 = clone x photoperiod interaction variance
- σ_{ST}^2 = clone x temperature interaction variance
- σ_{SP}^2 = between clone variance
- σ_{TP}^2 = between photoperiod variance
- σ_{UPS}^2 = between temperature variance

TABLE 10.2 MODEL FOR UNIVARIATE ANALYSIS OF VARIANCE IN EXPERIMENT 2 AND ESTIMATION OF OBSERVATIONAL COMPONENTS OF VARIANCE ASSUMING RANDOM TEMPERATURE AND FAMILY EFFECTS

Source	Degrees of Freedom	Mean Squares	Estimated Mean Squares
Temperatures (T)	$(NT - 1)$	MS_T	$\sigma_W^2 + WR\sigma_{FT}^2 + NSNR\sigma_T^2$
Families (F)	$(NS - 1)$	MS_F	$\sigma_W^2 + WR\sigma_{FT}^2 + NTNR\sigma_F^2$
Temperatures x Families	$(NT - 1)(NS - 1)$	MS_{TF}	$\sigma_W^2 + WR\sigma_{FT}^2$
Error	$NTNS(NR - 1)$	MS_W	σ_W^2
Total	$(NTNSNR - 1)$		

The meanings of some abbreviations are given in Tables 8.2 and 8.3 which describe the full analyses from which this specific model is derived. The others are:

MS_T = between temperatures mean square
 MS_F = between families mean square
 MS_{TF} = temperature x family interaction mean square
 MS_W = within family mean square
 σ_F^2 = between family variance
 σ_W^2 = within family variance
 σ_T^2 = between temperature variance
 σ_{TF}^2 = interaction variance

TABLE 10.3 UNIVARIATE ANALYSIS OF VARIANCE FOR DENSITY IN
EXPERIMENTS 1 AND 2

	Source	Degrees of Freedom	Mean Squares	Variance Ratios	Significance
Experiment 1 clones	Temperatures (<i>T</i>)	2	1.8920	>1000	***
	Photoperiods (<i>P</i>)	2	0.000363	2.2	*
	Clones (<i>S</i>)	9	0.031137	140	***
	<i>S</i> × <i>T</i>	18	0.000786	4.8	***
	<i>S</i> × <i>P</i>	18	0.000480	2.9	***
	<i>T</i> × <i>P</i>	4	0.001844	11.2	***
	<i>T</i> × <i>S</i> × <i>P</i>	36	0.000275	1.7	**
	Error	360	0.000164		
Experiment 2 half-sib seedlings	Temperatures (<i>T</i>)	4	1.4141	>1000	***
	Families (<i>F</i>)	19	0.003846	4.6	***
	<i>T</i> × <i>F</i>	76	0.001197	1.3	*
	Error	400	0.000844		

10.5 DISCUSSION

A discussion of these results, from a physiological point of view, will not be attempted. The experiments were conducted to obtain observational components of variance within and between clones and within and between half-sib seedlings which will be used in the next Chapter to estimate heritabilities.

In the absence of any data demonstrating the proportion of selfs, full sibs and half-sibs in *E. deglupta*, for estimating narrow sense heritability it will be necessary to assume the genetic relationship between related open pollinated progenies. *E. deglupta* is considered to be largely outcrossing and pollinated by insects and birds. The possibility of pollination by wind borne pollen cannot be discounted for pure, closely spaced stands. The habits and distances travelled by different pollinating vectors, which could complicate the system of pollination, are unknown. Differences in pollen production, viability and flowering time may also effect the number of contributing male parents (Boden, 1958).

CHAPTER 11

HERITABILITY

11.1 INTRODUCTION

Considerable variation in wood density and other parameters has been shown to be present in *Eucalyptus deglupta*. This variation is evident between trees and between geographic areas. However, such phenotypic variation is not proof of genotypic variation (Zobel, 1964). Properly designed and analysed clonal and seedling progeny tests are necessary to reliably determine the genetic component. However, there is sufficient quantitative information available from the environmental work in Chapter 10 to determine the degree of genetic control of wood density.

11.2 CALCULATION OF HERITABILITY

The notes and formulae have been taken from Allard (1960), Wright (1962) and Falconer (1964). Recent use of these techniques on *Eucalyptus regnans* has been made by Higgs (1969) and Eldridge (1969).

The quantitative assessment of genetic and environmental control for meristic characters is based on the apportioning of phenotypic variance (V_P) into that which is genetic and that which is non-genetic in origin, thus:

$$V_P = V_G + V_E$$

The genotypic variance (V_G) comprises additive (V_A), dominance (V_D) and interaction (V_I), components which measure variance of the breeding value, dominance deviation and epistatic deviation respectively, thus:

$$V_P = [V_A + V_D + V_I] + V_E$$

The additive variance is a statistical measure of the resemblance between relatives resulting from sexual propagation and, as a proportion of phenotypic variance (V_A/V_P), is termed the narrow sense heritability. This can be used for predicting the response to selection.

The dominance variance is a measure of the intra-allelic interaction while the epistatic variance measures interallelic interaction plus any linkage. This non-additive genotypic variance may be useful for an improvement programme based on vegetative propagation or on interspecific and interecotypic hybridization. The total genotypic variance as a proportion of phenotypic variance (V_G/V_P) is termed broad sense heritability.

A factor which inflates the phenotypic variance in an experiment is the genotype-environment correlation, i.e., the genotypic values and environmental deviations are not independent as is assumed in the foregoing equation. Competition between trees may partly result from genotype-environment correlation. It also biases the estimate of genotypic variance but this aspect is not fully understood and warrants a greater research effort (Stern, 1964).

Another important factor which may influence phenotypic variance is the genotype x environment interaction. This is

expressed if a specific difference in environment has different effects on different genotypes. When large changes in environment are involved, such as between different habitats, the genotype x environment interaction component may considerably influence the average genotypic response and should be regarded as part of the environmental variance (Namkoong *et al*, 1966). If favourable, this type of variance may be extremely useful since a desirable genotype for a particular area may then be utilised by vegetative propagation.

11.3 ESTIMATION OF NARROW SENSE HERITABILITY

The resemblance between relatives is estimated by partitioning the phenotypic variance into observational components corresponding to the grouping of progenies into families. Denoting the within family variance as σ_W^2 and the between family component as σ_B^2 , the degree of resemblance between relatives can be expressed as

$$\frac{\sigma_B^2}{\sigma_B^2 + \sigma_W^2}$$

which is known as the intraclass correlation coefficient (t).

The between family variance is also known as the phenotypic covariance of relatives and comprises both genotypic and environmental components, but the environmental covariance component resulting from a common environmental effect on related progenies is considered to be of minor importance with plants.

The genotypic co-variance of relatives is composed of the causal variance components in varying amount depending on the relationship between relatives. The co-variances for half sibs (progenies having one common parent) is as follows:

$$COV_{(HS)} = \frac{1}{4}V_A$$

Assuming the environmental co-variance of relatives to be zero, the phenotypic co-variance equals the genotypic co-variance of relatives. Then the phenotypic co-variance of relatives and the relationship between narrow sense heritability (h^2) and the intraclass correlation coefficient (t) for a half sib parent-progeny relationship is:

Phenotypic co-variance	Relationship of t to h^2
$\frac{1}{4}V_A$	$t = \frac{1}{4}h^2$

Using the notation of the components of variance given in the model in Table 10.2 narrow sense heritability

$$h_{NS}^2 = \frac{4\sigma_F^2}{\sigma_F^2 + \sigma_{TF}^2 + \sigma_W^2}$$

The calculation of narrow sense heritability is explained in Table 11.1. The variance components are derived from Table 10.3 (Experiment 2).

TABLE 11.1 CALCULATION OF NARROW SENSE HERITABILITY (h^2_{NS}) FOR WOOD DENSITY

$$\sigma^2_W = MS_W = 0.000844$$

$$\sigma^2_F = \frac{MS_F - MS_{TF}}{5} = 0.000106$$

$$\sigma^2_{TF} = \frac{MS_{TF} - \sigma^2_W}{5} = 0.000071$$

$$h^2_{NS} = \frac{4\sigma^2_F}{\sigma^2_F + \sigma^2_{TF} + \sigma^2_W} = 0.44$$

Standard error of the heritability estimate was calculated from the mean squares for families, families x temperatures and replications using the computer programme given by Eldridge (1969).

$$S.E. \text{ of } h^2_{NS} = 0.23$$

11.4 ESTIMATION OF BROAD SENSE HERITABILITY

The resemblance between clones is estimated by partitioning the observational components of variance corresponding to the grouping of plants into clones. If the within clone variance is denoted by σ_W^2 and the between clone component as σ_B^2 , the degree of resemblance between clones can be expressed as

$$\frac{\sigma_B^2}{\sigma_B^2 + \sigma_W^2}$$

Using the notation of the components of variance given in the model in Table 10.1

$$\text{broad sense heritability } h_{BS}^2 = \frac{\sigma_S^2}{\sigma_W^2 + \sigma_{TPS}^2 + \sigma_{ST}^2 + \sigma_{SP}^2 + \sigma_S^2}$$

The calculation of broad sense heritability is explained in Table 11.2. The variance components are derived from Table 10.3 (Experiment 1).

TABLE 11.2 CALCULATION OF BROAD SENSE HERITABILITY (h_{BS}^2) FOR WOOD DENSITY

$$\sigma_W^2 = MS_W = 0.000164$$

$$\sigma_{ST}^2 = \frac{MS_{ST} - MS_{TPS}}{15} = 0.000038$$

$$\sigma_{SP}^2 = \frac{MS_{SP} - MS_{TPS}}{15} = 0.000014$$

$$\sigma_{TPS}^2 = \frac{MS_{TPS} - MS_W}{5} = 0.000022$$

$$\sigma_S^2 = \frac{MS_S - MS_{ST} - MS_{SP} + MS_{TPS}}{45} = 0.000495$$

$$h_{BS}^2 = \frac{\sigma_S^2}{\sigma_W^2 + \sigma_{TPS}^2 + \sigma_{ST}^2 + \sigma_{SP}^2 + \sigma_S^2} = 0.68$$

$$S.E. \text{ of } h_{BS}^2 = 0.17$$

11.5 DISCUSSION

Wood density in *E. deglupta* appears sufficiently heritable to enable its manipulation by selection. However, these small experiments, using seedling material, can only be used as a guide.

Heritability is a parameter for a particular experiment, applying only for the specific environmental conditions and the specific population from which the sample of parents is drawn. The precision of the heritability estimate is strongly influenced by the sample variance. A greater number of clones and half-sib seedlings than was used here would be required to improve the precision of the estimate of heritability.

Since vegetative propagation in conjunction with tree selection offers the opportunity to secure a high genetic gain more quickly than by sexual propagation in this species, the relatively high broad sense heritability estimate for wood density will be of considerable importance to a tree improvement programme.

CHAPTER 12

WOOD DENSITY AND TREE SELECTION IN A TREE IMPROVEMENT PROGRAMME
FOR *EUCALYPTUS DEGLUPTA*

12.1 INTRODUCTION

The usefulness of wood density to characterize the wood of *Eucalyptus deglupta* has been established. The parameter is seen to have a high heritability value and should be a useful selection parameter in a tree improvement programme.

A change in wood density will not cause a similar change in money value of the product because not all facets of harvesting and manufacturing are altered in the same direction.

Assuming pulping and papermaking is the end use an increase in wood density would

- i. decrease handling costs for a given weight of wood;
- ii. decrease storage and transport costs for a given weight of wood;
- iii. Increase debarker yield for a given volume of wood;
- iv. Increase the cost of chipping a given volume of wood;
- v. Increase yield per cook in batch digesters;
- vi. decrease digestion costs because of greater weight of wood per charge;
- vii. Increase yield from a given volume of wood;
- viii. decrease refining time to a standard freeness and
- ix. decrease sheet density and affect paper strength properties.

Many of these effects vary with the process used and the significance of wood density would vary also depending on whether wood is purchased on a green volume, green weight or dry weight basis.

Breeding efforts to improve wood density for specific end uses cannot be evaluated without precise estimates of values for the processed products, information not presently available. The main criterion should be increased uniformity in wood density between trees. There is a possibility of dividing the density range into approximately three classes. The lower class could be used for peeling, the medium for pulping and the higher for sawn timber. Pre-selection on the basis of tree form is necessary to decrease the proportion of crooked, fluted or buttressed trees of *E. deglupta* in plantations. The trees selected in this stage have been termed 'candidate' trees. The second stage considers wood density. The desirable trees selected in the second stage have been termed 'plus' trees.

The inclusion of the pre-selection stage, using external characteristics, necessitated a study of the effects of this selection on wood density. In this Chapter a random set of trees has been investigated to determine the relationship between density and the candidate selection parameters.

The candidate trees and plus trees are then compared with this random set to determine the effect of candidate selection on wood density.

12.2 VARIABLES MEASURED ON STANDING TREES FOR CANDIDATE SELECTION AND COMPARISON WITH THE RANDOM POPULATION

(a) Diameter at breast height

This was determined over bark to the nearest 0.01 inch (0.025 mm).

(b) Total height

Total tree height was calculated from the mean of two estimations of angle of elevation using an Abney level (Forestry and Timber Bureau, 1964).

(c) Length of branch-free bole

This was determined using the same method as for (b).

(d) Crown depth

Crown depth was calculated by subtracting length of branch-free bole (c) from total height (b).

(e) Crown diameter

Crown diameter was the mean of two diameter measurements at right angles to each other, made on the vertical projection of the crown on the ground. The vertical projection was achieved with the help of a plumbob.

(f) Bole straightness

This was assessed on a points basis. Points were awarded subjectively with the aid of photographs (Plate 12.1) according to the following scale:

Very straight	30
Slight sweeps and kinks	20
Moderate sweeps and kinks	10
Severe sweeps and kinks	0

All subjective points assessment was carried out by the author to try and ensure uniformity in analysis.

(g) Bole cross-section shape (fluting)

This was also assessed on a point scoring system (Plate 12.2).

No fluting - bole cross-section circular	15
Very slight fluting	10-12
Slight fluting	8
Moderate fluting	5
Severe fluting	0

(h) Degree of buttressing

Points were allocated for this character (Plate 12.3).

Buttress terminating less than 1 foot (0.3 m) from ground level	5
Buttress terminating less than 2 feet (0.6 m) from ground level	4
Buttress terminating less than 3 feet (0.9 m) from ground level	3



PLATE 12.1 For straightness, the tree on the left would score 25 points, the one on the right would score less than 5 points.

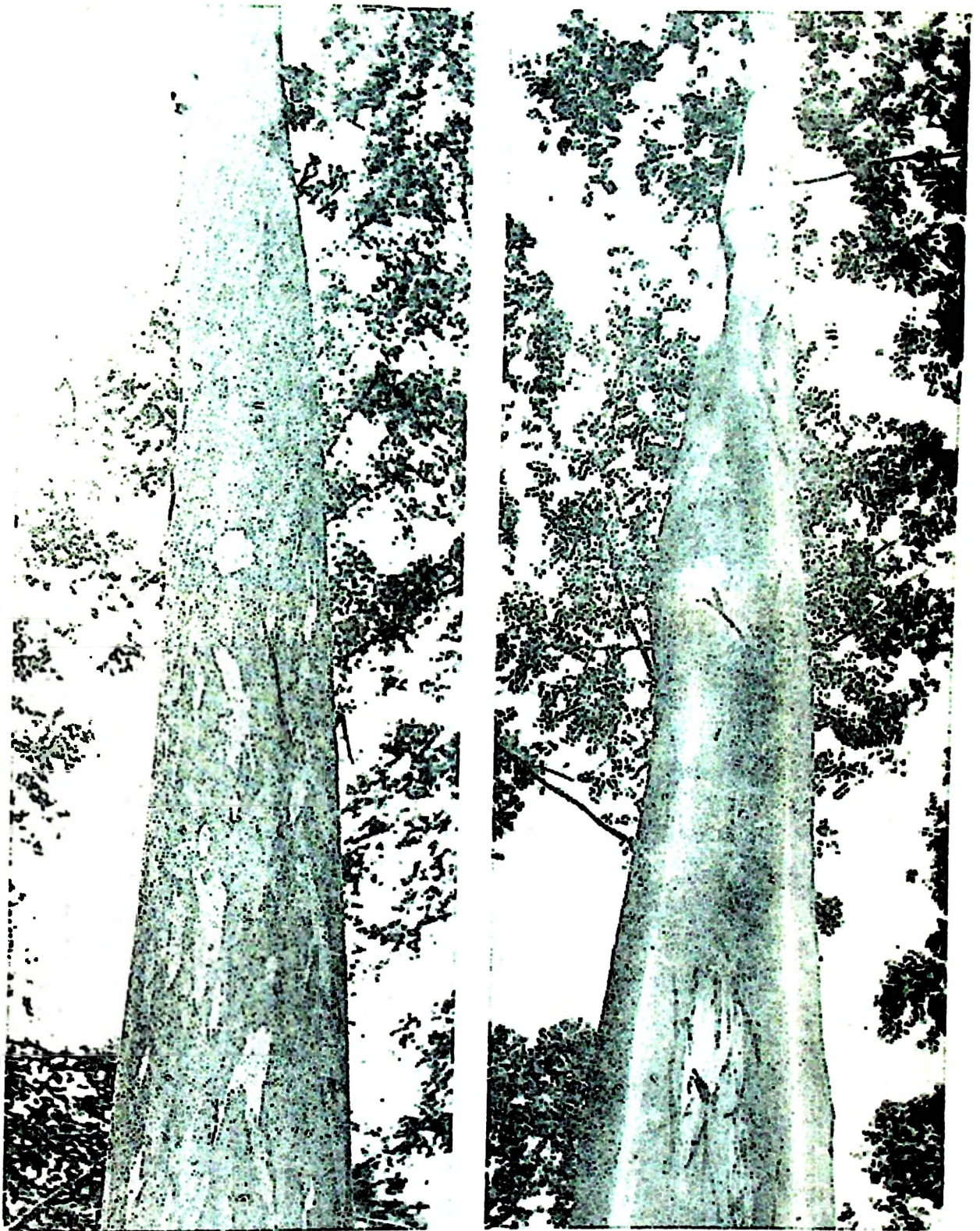


PLATE 12.2 The tree on the left would be awarded a high score for a nearly cylindrical bole. The one on the right is severely fluted and would receive nil points.

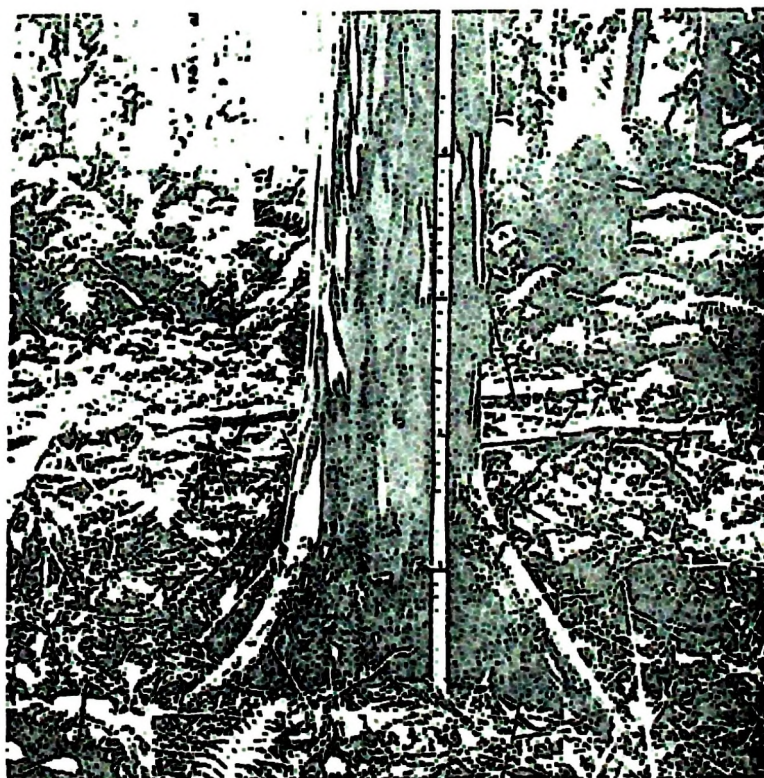
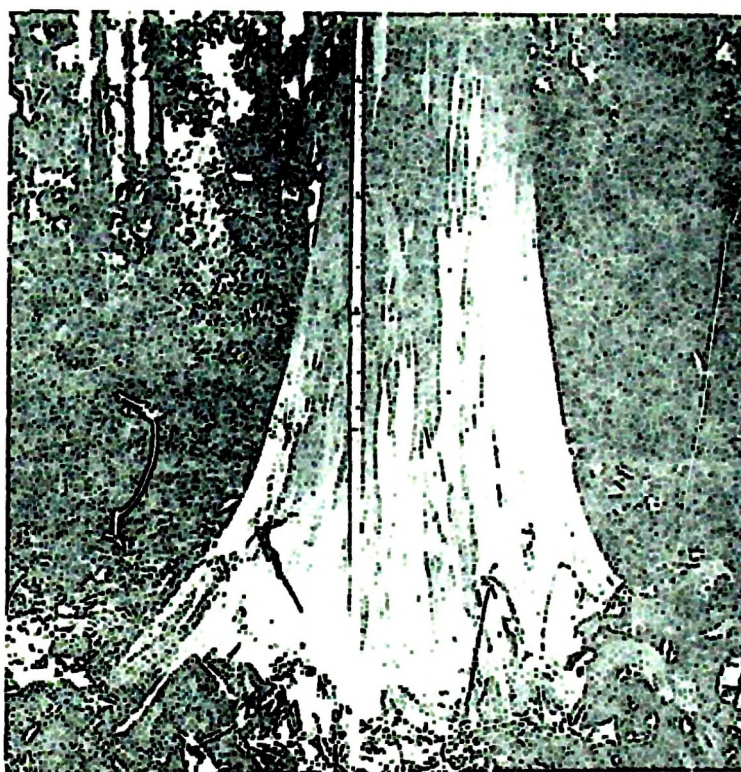


PLATE 12.3 Top: Buttressing extending more than five feet up the trunk.
Bottom: Buttressing extending less than two feet up the trunk.

Buttress terminating less than 4 feet (1.2 m) from ground level	2
Buttress terminating less than 5 feet (1.5 m) from ground level	1
Buttress terminating at a height greater than 5 feet (1.5 m) from ground level	0

(i) Crown shape and density

A healthy, deep cylindrical crown was sought. From zero to five points were awarded subjectively.

(j) Branch size and self-pruning ability

Small branches growing close to the horizontal attitude were sought. The bole was required to be free of un-extruded branch stubs up to the height of the first green branch other than epicormic. From zero to five points were awarded subjectively.

(k) Crown diameter to depth ratio

This parameter was derived from (d) and (e).

(l) Underbark volume of trunk to 4 in (10 cm) diameter top

Total volume under bark was calculated from the following formula taken from an unpublished volume table for *E. deglupta*.

$$V_T = -6.194 + 0.16H + 0.002823D^2H - 0.001151H^2 - 0.00000334D^2H^2$$

where V_T = total volume (cu ft)

H = height (ft)

D = breast height diameter (in)

Volume to 4 in (10 cm) diameter top was then obtained using the following equation

$$V_4 = V_T (0.9923 + (-4.2986 (2.7183^{-0.5039D}))$$

where V_4 = volume to 4 in diameter top (cu ft)

V_T = total volume (cu ft)

D = breast height diameter (in).

Using the equipment described by Sulc (1967) a bark to pith sample, one inch (2.5 cms) square in cross-section, was removed from the standing tree at ten per cent of total height (Plate 12.4). The reason for using this height was explained in Chapter 7.

(m) Weight of wood fibre in the trunk

This was derived from density, and trunk volume in the following way

$$F_W = (DENS \times 62.5) \times V_4$$

where F_W = fibre weight (lbs)

$DENS$ = wood density (gms/cc)

V_4 = volume to 4 in diameter top (cu ft)

62.5 = weight of one cubic foot of water (lbs) having a density 1.00 gms/cc

12.3 EXPERIMENTAL MATERIAL

Random population trees and candidate trees were selected from plantation stands at Keravat, New Britain (Table 12.1). The random population trees were located in groups of five by dividing a map of the compartments into numbered grid squares and choosing squares by consulting random number tables. The locations chosen were then found in the field. The candidate trees were each chosen subjectively as being superior in growth and morphological characters to the 5-10 trees nearby. Most of the trees were between 14 and 16 years old at the time of selection (140 of 150 candidates, 75 of 125 random). Stocking and spacing were similar in all compartments. The parameters described in Section 12.2 and listed in Table 12.2 were assessed for each tree.

12.4 COMPARISON BETWEEN PARAMETER STATISTICS OBTAINED FOR CANDIDATE AND RANDOM POPULATIONS

A comparison between the dispersion statistics of some measured parameters of candidate and random population trees is made in Table 12.3.

The assessment scores for buttressing, (x_{49}) crown characteristics (x_{50}) and branch size and angle (x_{51}) were significantly non-normal at the five per cent probability level in both candidate and random populations. This leads to the possibility that the subjective estimations were biased. For the remaining parameters, there was insufficient evidence to reject the null hypothesis that the distributions approximated normality.

TABLE 12.1 ORIGIN OF EXPERIMENTAL TREES, KERA VAT, NEW BRITAIN

Compartment	Year Planted	Area (acres)	Candidate Numbers	Random Tree Numbers
Station	1948	4	1-5	1-25
Fryar 1	1950/51	10	6	-
Fryar 7	1952/53	18	7	-
Fryar 9	1952/53	14	8, 9	26-40
Fryar 11	1952/53	23	29	41-50
Fryar 13	1953/54	60	10-22, 35-46	51-75
Fryar 14	1954/55	118	23-28, 30-34, 47-113	76-100
Fryar 15	1955/56	56	114-150	100-125



PLATE 12.4 Sampling for wood quality in standing trees of *E. deglupta*. The gimbal for the sampling machine (see Sulc, 1967) is being attached at a point 5 m above ground (10 per cent of total tree height).

TABLE 12.2 LIST OF PARAMETERS ASSESSED ON STANDING TREES

Measured or estimated

x_{43} (DBH)	Diameter breast height over bark
x_{44} (THT)	Total height
x_{45} (BHT)	Length of branch free bole
x_{46} (MCD)	Mean crown diameter
x_{47} (STRT)	Score for degree of stem straightness
x_{48} (FLUT)	Score for degree of stem fluting
x_{49} (BUTT)	Score for degree of stem buttress
x_{50} (CRN)	Score for crown characteristics such as density and shape
x_{51} (BRCH)	Score for branch size, angle and self-pruning ability
x_{52} (DENS)	Whole tree wood density

Derived

x_{53} (DPTH)	Crown depth (from x_{44} and x_{45})
x_{54} (VOL)	Volume under bark (from x_{43} and x_{44})
x_{55} (WT)	Weight (from x_{52} and x_{54})
x_{56} (CRAR)	Area of crown projected on the ground (from x_{46})
x_{57} (RCDA)	Ratio crown depth to crown area projected on the ground (from x_{44} , x_{45} and x_{53})

The selection of candidate trees has been successful in improving most characters in the desired direction. The candidates have, on the average, a 1.44 inch (3.66 cm) diameter, a 6.7 feet (2.0 m) height and a 4.9 feet (1.5 m) bole length advantage over the normal population (Table 12.3). The candidates are much straighter and have less fluting of the stem cross-section than the random population (Table 12.3). However, mean wood density has been reduced from 0.36 to 0.34 gms/cc, but more desirable trees have been obtained by this pre-selection based on tree size and form for only a one per cent penalty in wood density.

The coefficients of variation (Table 12.3) indicate that breast height, diameter, total height, crown diameter, straightness and fluting parameters are more uniform while wood density is only slightly more uniform and length of branch-free bole is barely changed in the candidate population.

12.5 PRINCIPAL COMPONENT AND FACTOR ANALYSES FOR THE CANDIDATE AND PLUS TREE POPULATIONS

A matrix of correlation coefficients for parameters measured on the random population is given in Table 12.4. Wood density is correlated with trunk diameter at breast height, mean crown diameter, volume of trunk, weight of trunk and area of projection of crown on the ground at the 0.1 per cent level of probability. The latter three of these correlations are high because they were derived from the first three variables mentioned.

In order to clearly understand the associations between variables principal components were derived (Table 12.5). This analysis shows that wood density occurs prominently only in the fourth component

TABLE 12.4 MATRIX OF CORRELATION COEFFICIENTS BETWEEN PARAMETERS MEASURED ON RANDOM POPULATION TREES

	x_{43}	x_{44}	x_{45}	x_{46}	x_{47}	x_{48}	x_{49}	x_{50}	x_{51}	x_{52}	x_{53}	x_{54}	x_{55}	x_{56}	x_{57}
x_{43} (DBH)	1.00	***	***	***	*	NS	***	*	NS	***	***	***	***	***	NS
x_{44} (TBT)	0.72	1.00	***	***	NS	NS	***	NS	NS	NS	***	***	***	***	NS
x_{45} (BBT)	0.28	0.52	1.00	NS	NS	**	***	***	NS	NS	***	***	***	NS	***
x_{46} (MCD)	0.72	0.35	-0.03	1.00	**	NS	***	***	NS	***	***	***	***	***	**
x_{47} (SEXT)	0.19	-0.03	0.12	0.26	1.00	**	*	**	**	NS	NS	*	NS	**	NS
x_{48} (FLUT)	0.01	0.07	0.24	0.08	0.25	1.00	NS	NS	*	NS	**	NS	NS	NS	*
x_{49} (BUTT)	-0.66	-0.48	-0.30	-0.35	-0.16	0.11	1.00	NS	NS	**	NS	***	***	***	NS
x_{50} (CRN)	0.18	-0.00	-0.23	0.42	0.26	0.09	0.02	1.00	***	NS	**	NS	NS	***	NS
x_{51} (BRCH)	-0.03	0.08	0.09	-0.01	0.23	0.18	0.06	0.43	1.00	*	NS	NS	NS	NS	NS
x_{52} (DENS)	0.35	0.14	-0.03	0.39	0.06	-0.08	-0.24	0.01	-0.20	1.00	*	***	***	***	NS
x_{53} (DEPTH)	0.33	0.31	-0.65	0.34	-0.05	-0.21	-0.09	0.26	-0.03	0.16	1.00	***	***	***	***
x_{54} (VOL)	0.98	0.72	0.30	0.67	0.16	0.00	-0.68	0.08	-0.07	0.35	0.31	1.00	***	***	NS
x_{55} (WT)	0.96	0.68	0.27	0.67	0.15	-0.01	-0.68	0.05	-0.11	0.46	0.31	0.99	1.00	***	NS
x_{56} (CRAR)	0.70	0.34	0.00	0.98	0.24	0.08	-0.35	0.35	-0.06	0.38	0.30	0.67	0.68	1.00	**
x_{57} (RCDA)	-0.11	0.08	-0.64	-0.24	-0.15	-0.19	0.13	-0.01	-0.02	-0.08	0.79	-0.10	-0.10	-0.25	1.00

* $r > 0.16$ significant at the five per cent probability level** $r > 0.21$ significant at the one per cent probability level*** $r > 0.27$ significant at the 0.1 per cent probability level

NS Not significant at the five per cent probability level

TABLE 12.5 RESULTS OF PRINCIPAL COMPONENT ANALYSIS ON PARAMETERS
MEASURED ON RANDOM POPULATION TREES

Component or eigen vector number	1 (ξ_1)	2 (ξ_2)	3 (ξ_3)	4 (ξ_4)
Eigen values	5.57	2.58	1.92	1.40
Cumulative percentage of eigen values	37.1	54.3	67.2	76.5
Percentage of total eigen values in each component	37.1	17.2	12.8	9.4
x_{43} (DBH)	<u>+0.41</u>	-0.00	-0.05	+0.09
x_{44} (THT)	<u>+0.30</u>	-0.08	-0.20	+0.44
x_{45} (BHT)	+0.11	<u>-0.55</u>	-0.12	+0.20
x_{46} (MCD)	+0.35	+0.09	+0.28	<u>-0.25</u>
x_{47} (STRT)	+0.10	-0.08	<u>+0.41</u>	-0.00
x_{48} (FLUT)	+0.01	-0.22	<u>+0.31</u>	+0.18
x_{49} (BUTT)	<u>-0.29</u>	+0.10	+0.18	-0.09
x_{50} (CRN)	+0.09	+0.17	<u>+0.54</u>	+0.08
x_{51} (BRCH)	-0.02	-0.05	<u>+0.42</u>	+0.49
x_{52} (DENS)	+0.19	+0.07	-0.08	<u>-0.43</u>
x_{53} (DPTH)	+0.14	<u>+0.56</u>	-0.04	+0.17
x_{54} (VOL)	<u>+0.41</u>	-0.02	-0.11	+0.09
x_{55} (WT)	<u>+0.41</u>	-0.01	-0.13	+0.02
x_{56} (CRAR)	+0.34	+0.07	+0.22	-0.28
x_{57} (RCDA)	-0.06	<u>+0.52</u>	-0.17	+0.33

Important variables in each component were determined by rotated factor analysis (Table 12.6) and are underlined.

TABLE 12.6 ROTATED FACTOR MATRIX SHOWING CORRELATIONS OF VARIABLES MEASURED ON RANDOM POPULATION TREES WITH THE FOUR COMPONENTS IN TABLE 12.5

	F_1	F_2	F_3	F_4
x_{43} (DBH)	<u>+0.87</u>	+0.04	+0.11	-0.42
x_{44} (THT)	<u>+0.91</u>	+0.05	+0.06	+0.12
x_{45} (BHT)	+0.50	<u>-0.79</u>	+0.02	+0.25
x_{46} (MCD)	+0.42	+0.07	+0.31	<u>-0.80</u>
x_{47} (STRT)	+0.03	-0.13	<u>+0.56</u>	-0.26
x_{48} (FLUT)	+0.02	-0.32	<u>+0.49</u>	+0.08
x_{49} (BUTT)	<u>-0.71</u>	+0.10	+0.08	+0.19
x_{50} (CRN)	-0.05	+0.26	<u>+0.73</u>	-0.29
x_{51} (BRCH)	+0.04	+0.03	<u>+0.76</u>	+0.33
x_{52} (DENS)	+0.18	+0.01	-0.24	<u>+0.63</u>
x_{53} (DPTH)	+0.26	<u>+0.93</u>	+0.03	-0.17
x_{54} (VOL)	<u>+0.89</u>	+0.02	+0.03	-0.39
x_{55} (WT)	<u>+0.86</u>	+0.02	-0.03	-0.45
x_{56} (CRAR)	+0.42	+0.04	+0.26	<u>-0.80</u>
x_{57} (RCDA)	+0.00	<u>+0.90</u>	-0.11	+0.29

Important correlations are underlined. These are used to determine the important members of the components in Table 12.5.

$$F_i = \epsilon_i \cdot \lambda_i^{-0.5}$$

representing 9.4 per cent of the total variation in the system. Importantly, it is independent of the production parameters such as diameter, height and volume (first component, Table 12.5 and Table 12.6). This indicates that density could be manipulated by tree breeding without markedly affecting volume production. Breeding for a higher density would mean more useable wood per hectare.

The preselection on the basis of tree size and form changes the correlations between parameters only slightly (compare Table 12.7 with Table 12.4). However, the principal component and factor analyses (Tables 12.8 and 12.9) indicate that density has assumed a greater proportion of the total variation and now appears in the second component representing 17.9 per cent of the total variation. This means that density in the candidate trees is relatively more variable, compared with the production variables, than in the random population. This is because the preselection based on some of these production variables has tended to make them more uniform.

It is possible to select a narrow range of whole tree densities without markedly affecting the production variables. Tables 12.10 and 12.11 show the results of principal component and factor analyses on 36 trees selected within a whole tree density range of 0.36 to 0.40 gms/cc. Production variables remain unaffected in the first component while density appears alone in a fifth component representing only 6.9 per cent of the variation in the system. This is a direct result of narrowing the density range, leading to increased uniformity in density between trees.

The three sets of analyses (Tables 12.4 to 12.11), taken together, illustrate how density may vary while the first component of variability, containing production variables, is almost unaffected.

TABLE 12.7 MATRIX OF CORRELATION COEFFICIENTS BETWEEN PARAMETERS MEASURED ON CANDIDATE POPULATION TREES

	x_{43}	x_{44}	x_{45}	x_{46}	x_{47}	x_{48}	x_{49}	x_{50}	x_{51}	x_{52}	x_{53}	x_{54}	x_{55}	x_{56}	x_{57}
x_{43} (DBH)	1.00	***	***	***	*	NS	***	NS	NS	*	***	***	***	***	NS
x_{44} (TEXT)	0.74	1.00	***	***	**	NS	***	NS	***	**	**	***	***	***	NS
x_{45} (BET)	0.33	0.70	1.00	NS	*	*	***	**	***	***	***	***	***	NS	***
x_{46} (MCD)	0.66	0.28	-0.09	1.00	NS	NS	**	**	*	NS	***	***	***	***	***
x_{47} (STRT)	0.20	0.26	0.20	0.14	1.00	***	NS	NS	***	NS	NS	**	*	NS	NS
x_{48} (FLUT)	0.14	0.11	0.16	0.10	0.38	1.00	NS	**	***	NS	NS	NS	NS	NS	NS
x_{49} (BUTT)	-0.44	-0.43	-0.31	-0.21	-0.01	0.14	1.00	NS	NS	*	NS	***	***	**	NS
x_{50} (CRN)	0.09	-0.11	-0.22	0.22	0.11	0.22	0.09	1.00	NS	NS	*	NS	NS	*	NS
x_{51} (BRCH)	-0.01	0.28	0.40	-0.18	0.28	0.34	-0.04	0.03	1.00	**	**	NS	NS	*	NS
x_{52} (DENS)	-0.16	-0.23	-0.27	0.09	-0.14	-0.03	0.20	-0.01	-0.24	1.00	NS	*	NS	NS	NS
x_{53} (DEPTH)	0.41	0.22	-0.55	0.44	0.02	-0.02	-0.08	0.17	-0.22	0.10	1.00	***	***	***	***
x_{54} (VOL)	0.98	0.75	0.37	0.66	0.21	0.10	-0.45	0.03	0.02	-0.17	0.38	1.00	***	***	NS
x_{55} (WT)	0.96	0.73	0.32	0.69	0.20	0.10	-0.42	0.03	-0.02	0.03	0.41	0.98	1.00	***	NS
x_{56} (CRAR)	0.67	0.28	-0.08	0.99	0.13	0.09	-0.21	0.20	-0.16	0.07	0.44	0.68	0.71	1.00	***
x_{57} (RCDA)	-0.09	0.02	-0.46	-0.36	-0.08	-0.13	0.06	-0.01	-0.06	0.01	0.65	-0.10	-0.10	-0.33	1.00

* $r > 0.16$ significant at the five per cent probability level** $r > 0.21$ significant at the one per cent probability level*** $r > 0.27$ significant at the 0.1 per cent probability level

NS Not significant at the five per cent probability level

TABLE 12.8 RESULTS OF PRINCIPAL COMPONENT ANALYSIS ON PARAMETERS
MEASURED ON CANDIDATE POPULATION TREES

Component or eigen vector number	1 (ξ_1)	2 (ξ_2)	3 (ξ_3)	4 (ξ_4)
Eigen values	5.25	2.68	1.73	1.61
Cumulative percentage of eigen values	35.0	52.9	64.4	75.1
Percentage of total eigen values in each component	35.0	17.9	11.5	10.7
x_{43} (DBH)	<u>+0.42</u>	+0.01	-0.08	+0.02
x_{44} (THT)	<u>+0.33</u>	-0.24	-0.26	+0.11
x_{45} (BHT)	+0.15	<u>-0.53</u>	-0.05	-0.14
x_{46} (MCD)	<u>+0.34</u>	-0.24	+0.29	-0.14
x_{47} (STRT)	+0.12	-0.17	+0.23	+0.40
x_{48} (FLUT)	+0.07	-0.14	+0.39	<u>+0.43</u>
x_{49} (BUTT)	<u>-0.21</u>	+0.12	+0.29	+0.17
x_{50} (CRN)	+0.04	+0.16	+0.34	<u>+0.28</u>
x_{51} (BRCH)	+0.02	<u>-0.37</u>	+0.07	+0.37
x_{52} (DENS)	-0.06	<u>+0.25</u>	+0.16	-0.17
x_{53} (DPTH)	+0.18	+0.44	<u>-0.23</u>	+0.33
x_{54} (VOL)	<u>+0.42</u>	-0.01	-0.10	-0.01
x_{55} (WT)	<u>+0.42</u>	+0.04	-0.06	-0.04
x_{56} (CRAR)	<u>+0.34</u>	+0.23	+0.27	-0.14
x_{57} (RCDA)	-0.08	+0.25	<u>-0.51</u>	+0.45

Important variables in each component were determined by rotated factor analysis (Table 12.9) and are underlined.

TABLE 12.9 ROTATED FACTOR MATRIX SHOWING CORRELATIONS OF VARIABLES MEASURED ON CANDIDATE POPULATION TREES WITH THE FOUR COMPONENTS IN TABLE 12.8

	F_1	F_2	F_3	F_4
$x_{43}(DBH)$	<u>+0.94</u>	-0.21	-0.07	+0.07
$x_{44}(THT)$	<u>+0.66</u>	-0.65	-0.06	+0.00
$x_{45}(BHT)$	+0.23	<u>-0.75</u>	+0.55	-0.06
$x_{46}(MCD)$	<u>+0.84</u>	+0.41	+0.12	+0.20
$x_{47}(STRT)$	+0.15	-0.30	+0.02	+0.63
$x_{48}(FLUT)$	+0.04	-0.14	+0.09	<u>+0.78</u>
$x_{49}(BUTT)$	<u>-0.48</u>	+0.35	-0.02	+0.33
$x_{50}(CRN)$	+0.08	+0.29	-0.10	<u>+0.56</u>
$x_{51}(BRCH)$	-0.12	<u>-0.61</u>	+0.10	+0.45
$x_{52}(DENS)$	-0.03	<u>+0.52</u>	+0.03	-0.06
$x_{53}(DPTH)$	+0.46	+0.26	<u>-0.82</u>	+0.08
$x_{54}(VOL)$	<u>+0.94</u>	-0.24	-0.05	+0.03
$x_{55}(WT)$	<u>+0.95</u>	-0.14	-0.04	+0.03
$x_{56}(CRAR)$	<u>+0.85</u>	-0.39	+0.11	+0.18
$x_{57}(RCDA)$	-0.18	-0.11	<u>-0.96</u>	-0.10

Important correlations are underlined. These are used to indicate the important members of the components in Table 12.8.

$$F_i = \xi_1 \cdot \lambda_i^{-0.5}.$$

TABLE 12.10 RESULTS OF PRINCIPAL COMPONENT ANALYSIS ON PARAMETERS
MEASURED ON 36 PLUS TREES SELECTED FROM THE CANDIDATE
POPULATION AND HAVING WOOD DENSITIES IN THE RANGE
0.36-0.40 gms/cc

Component or eigen vector number	1 (ξ_1)	2 (ξ_2)	3 (ξ_3)	4 (ξ_4)	5 (ξ_5)
Eigen values	5.24	2.60	2.21	1.19	1.04
Cumulative percentage of eigen values	34.9	52.3	67.0	74.9	81.8
Percentage of total eigen values in each component	34.9	17.4	14.7	7.9	6.9
x_{43} (DBH)	<u>+0.40</u>	+0.04	+0.08	-0.11	+0.18
x_{44} (THT)	<u>+0.34</u>	-0.22	+0.24	-0.03	-0.14
x_{45} (BHT)	+0.19	<u>-0.53</u>	-0.04	-0.16	-0.03
x_{46} (MCD)	+0.25	+0.38	<u>-0.28</u>	-0.23	-0.16
x_{47} (STRT)	+0.25	-0.12	-0.10	<u>+0.34</u>	-0.43
x_{48} (FLUT)	+0.21	-0.18	-0.28	<u>+0.45</u>	-0.12
x_{49} (BUFT)	<u>-0.11</u>	+0.15	-0.28	+0.32	-0.14
x_{50} (CRN)	+0.22	+0.08	-0.40	+0.26	+0.05
x_{51} (BRCH)	+0.14	-0.21	-0.19	+0.30	+0.01
x_{52} (DENS)	+0.07	+0.06	+0.10	+0.29	<u>+0.79</u>
x_{53} (DPTH)	+0.14	<u>+0.46</u>	-0.22	+0.18	-0.12
x_{54} (VOL)	<u>+0.42</u>	-0.00	+0.34	-0.12	+0.10
x_{55} (WT)	<u>+0.42</u>	+0.01	+0.10	-0.09	+0.18
x_{56} (CRAR)	-0.25	<u>+0.38</u>	-0.28	-0.21	-0.12
x_{57} (RCDA)	0.02	<u>+0.23</u>	+0.55	+0.39	+0.01

Important variables in each component were determined by rotated factor analysis (Table 12.11) and are underlined.

TABLE 12.11 ROTATED FACTOR MATRIX SHOWING CORRELATIONS OF VARIABLES
MEASURED ON 36 PLUS TREES WITH THE FIVE COMPONENTS IN
TABLE 12.10

	F_1	F_2	F_3	F_4	F_5
x_{43} (DBH)	<u>+0.81</u>	+0.09	-0.41	+0.23	+0.20
x_{44} (THT)	<u>+0.83</u>	+0.04	+0.02	+0.40	-0.19
x_{45} (BHT)	+0.58	<u>-0.63</u>	+0.28	+0.35	-0.12
x_{46} (MCD)	+0.12	+0.03	<u>-0.96</u>	+0.08	+0.02
x_{47} (STRT)	+0.21	-0.01	-0.18	<u>+0.78</u>	-0.19
x_{48} (FLUT)	+0.07	-0.21	-0.10	<u>+0.81</u>	+0.18
x_{49} (BUTT)	<u>-0.68</u>	-0.08	-0.26	+0.27	+0.15
x_{50} (CRN)	+0.13	+0.04	-0.34	+0.45	+0.28
x_{51} (BRCH)	+0.30	+0.04	+0.24	+0.44	+0.07
x_{52} (DENS)	+0.01	-0.05	-0.05	+0.06	<u>+0.94</u>
x_{53} (DPTH)	+0.19	<u>+0.90</u>	-0.38	-0.01	-0.06
x_{54} (VOL)	<u>+0.85</u>	+0.07	-0.37	+0.28	+0.11
x_{55} (WT)	<u>+0.84</u>	+0.06	-0.38	+0.28	+0.21
x_{56} (CRAR)	+0.12	+0.04	<u>-0.95</u>	+0.08	+0.07
x_{57} (RCDA)	+0.11	<u>+0.94</u>	+0.30	-0.05	-0.03

Important correlations are underlined. These are used to indicate the important members of the components in Table 12.10.

$$F_i = \xi_1 \cdot \lambda_i^{-0.5}$$

CHAPTER 13

DISCUSSION

Total forest area in tropical and sub-tropical zones*, according to the F.A.O. World Forest Inventory of 1963, was about 2,430 million hectares. The estimate is inflated because open savannah is included as 'forest', nevertheless these zones do represent a huge forest resource.

Practical use of this resource is subject to serious limitations. Great centres of population in India, China and elsewhere are devoid of forests, while large areas of lowland tropical rainforest such as the Amazon Basin (240 million hectares), West Central Africa and Southeastern Asia are sparsely inhabited. Further, the luxuriant tropical rainforest consists of a great variety of species of which only a few are known to be commercially valuable. These two limitations are aggravated in the developing countries† by lack of technological achievements with which to overcome them.

*For all practical purposes the 'tropical and subtropical zones' of the world may be said to coincide with Latin America, Asia, Africa and the Pacific Region (Oceania); i.e., the regions outside North America, Europe and the U.S.S.R., but excluding Korea, Northern China, The Himalayas, The Andes and parts of Japan.

†If Southern China, Northern Australia, and Japan are excluded, the remaining countries in the subtropical and tropical zones may be loosely termed 'developing countries'.

The efforts of developing countries to raise their standard of living by using their natural resources to support industrial development have focussed on the forest resource and particularly on the exploitation of the broad-leaved natural forest in these regions. This has meant selective exploitation of the few species in demand for an export market. Present views favour the conversion of tropical and subtropical wood to pulp as one of the surest means of industrial development and this criterion should remain in the future.

The manufacture of pulp, paper and other reconstituted wood products from most tropical hardwoods has inherent technological difficulties. This has stimulated interest in the establishment of plantations of quick growing species which are more suitable as a raw material for reconstituted products. This development has further operational advantages in that plantations can be sited to offset difficulties of poor transport services and lack of community services in the developing countries.

In many regions, extensive areas have already been planted (Table 13.1) to meet wood requirements other than pulp. For example *Tectona grandis* L.f. has been planted as a valuable timber and veneer species. Many plantations are poorly sited in regard to environmental growth conditions and access of transport. Many of these present plantations, if not set aside for pulp or high value timber produce, will go towards more traditional uses such as local building construction and fuelwood.

F.A.O. has made an estimate of the additional requirements of plantation wood for the years 1975 and 2000 over the 1959-61 figures (Table 13.1) and has projected availability to the same dates.

TABLE 13.1 ESTIMATED ADDITIONAL ROUNDWOOD REQUIREMENTS FOR THE YEARS 1975 AND 2000 IN DEVELOPING COUNTRIES FOR PAPER AND PAPERBOARD, WOOD USE IN THE ROUND, FIBREBOARD AND PARTICLEBOARD. ALSO SHOWN ARE PLANTATION AREAS, RATE OF PLANTING AND YIELD EXPECTATIONS*

Region	Estimated additional requirements ^a for 1975		Area of existing plantations (1964)		Estimated annual yield as of 1975		Rate of Planting (1964)		Estimated additional requirements for year 2000 (for paper and paperboard)		Estimated annual yield as of year 2000 if current rate of plantation establishment is maintained	
	Paper and wood used in the round	Fibreboard and particleboard	Conifers	Broadleaved	Total	1000 hectares	Million m ³	Million ha/yr	Million m ³	Million m ³	Million m ³	Million m ³
Latin America	11.5	2.1	1.5	14.9	16.4	500	16.00	0.190	70	53	53	53
Near East	0.7	1.0	0.2	1.9	2.6	150	1.50	0.015	5	5	5	5
Asia-Pacific	7.2	4.7	0.5	12.4	15.0	135	16.50	0.120	45	46	46	46
Africa	2.4	3.8	0.3	6.5	9.75	735	9.75	0.050	20	22	22	22
Total	21.6	11.6	2.5	35.7	43.75	3470	43.75	0.335	140	126	126	126

Sources: F.A.O. Staff, Unanyia 1965, No. 79

a. Over 1959-61 average annual consumption

b. Estimates confined to paper and paperboard, the only product group for which meaningful predictions can be made this far into the future.

Estimates assume average rates of growth of 2.5 per cent per annum in population and 2 per cent per year in per capita income for each region. They further assume an average requirement of 2.75 cubic meters of roundwood per ton of paper and paperboard in each region.

These figures show that present trends in plantation establishment should guarantee an adequate internal supply of plantation wood by 1975. The situation takes on a forboding aspect when the perspective is extended to the year 2000, when internal consumption of paper and paperboard would have gained momentum. A generous estimate of future plantation yield does not meet even the projected additional requirements for paper and paperboard quite apart from other demands on wood.

The issue of the future position of the natural forests in the sub-tropical and tropical zones must also be raised. Although their aggregate area is immense, they are adversely treated by the pressure of the growing population for land by indiscriminate cutting for fuel and construction wood, by fire and by shifting cultivation and grazing, while exploitation of valuable export timber is carried on without any noteworthy regard to silvicultural requirements in many instances. Where silviculture is practiced, it is hampered by extreme difficulties in mixed hardwood forest against a host of competing species. In this way, only a fraction of the potential capacity of forest lands in the tropical and sub-tropical zones can be employed in growing useful wood and only at high cost. For these reasons, the natural tropical and sub-tropical forest cannot be relied upon to make a significant contribution to wood requirements after the 1980's.

The overall world supply situation becomes critical with the increasing difficulty of the industrialised nations of the world to meet their increasing demand for wood from their own resources (Table 13.2), and the need to provide large tracts of forest for watershed protection, fauna conservation and community use. The

**TABLE 13.2 EXPECTED CHANGE IN THE WORLD'S INDUSTRIAL WOOD
BALANCE 1961-1975 (MILLION CUBIC METERS OF ROUNDWOOD
AND WOOD RAW MATERIAL EQUIVALENT)***

Region	Consumption		Production		Surplus (+) or Deficit (-)	
	1961	1975	1961	1975	1961	1975
Europe	259.4	376	224.3 (238.3)†	272 (297)	-21.1	-79
U.S.S.R.	243.2	305	256.8 (259.0)		+15.8	
Canada	32.5	44	89.0		+56.5	
U.S.A.	288.0	376	250.3	326	-37.7	-50
Total North America	320.5	420	339.3		+18.8	
Latin America	39.9	76	38.5		-1.4	
Africa	25.0	36	25.6		+0.6	
Near East	9.5	14	6.4		-3.1	
Far East ¹	41.5	68	45.3		+3.8	
Japan	63.0	112	48.4 (52.6)	72 (82)	-10.4	-30
Mainland China	34.0	62	34.0			
Pacific	18.1	26	15.4 (16.1)	21 (22)	-2.0	
World	1054.1	1490	1034.0		+1.0	

*Source: Wood World Trends and Prospects, F.A.O., Unasylva, Number 80-81, 1966

†Figures in parenthesis show roundwood removals plus usable wood residues where data is available

¹Excluding Japan and Mainland China

three main deficit regions in regard to industrial wood shown in Table 13.2 are the U.S.A., Europe and Japan. The increasing deficit in the case of Japan has its nearest surplus regions in the Pacific North-West, and the adjacent parts of the U.S.S.R. So far the Pacific North-West, including Alaska, has been the main source of imported wood pulp and, in recent years, also of pulpwood to Japan. In regard to pulpwood, plantations of quick growing species in the tropical and sub-tropical countries bordering the Pacific Ocean should offer ample opportunities for Japan to meet her deficit. The fact that Japan already imports sawlogs and wood chips from some countries in this region seems to indicate the feasibility of such developments.

The small size of the present local market in many developing countries is a hindrance to profitable internal investment in the case of wood pulp industry. An attractive investment opportunity arises when one or a group of wood users in an industrial nation with a raw material deficit looks to other regions for supply, preferably by investing firstly in a wood chip operation and perhaps later in a pulp mill and re-forestation projects. This brings several advantages to the host country and solves the difficult questions of local pulp marketing and supply of skilled personnel. In return, the host country must satisfy the investor that there is minimal risk of political expropriation, and that an adequate supply of raw material on a long term basis is available. Even for short rotations of quick growing species, co-operation of Governments and Government Forest Departments are needed to solve possible initial difficulties of finance, research and management of plantations.

Papua and New Guinea is well situated among countries in the Pacific Region to take advantage of many of the factors mentioned. In Papua and New Guinea, however, species selection for afforestation and reafforestation has been a problem. On forested highland areas indigenous *Araucaria hunsteinii* and *A. cunninghamii* have been successful reafforestation species. On grassland areas, the only *Pinus* species which have shown promise are *P. caribaea* var. *bahamensis* (Barr and Gulf), *P. caribaea* var. *hondurensis* (Barr and Gulf), *P. kesiya* (= *Pinus khasya* Noyle ex Hook) and *P. merkusii* (Jung et de Vriese). The seed of *P. caribaea* is scarce and costly while the latter two species require provenance screening. On the forested tropical lowlands *Pinus* plantings are generally unsuccessful because their very slow early growth compared with competing broad leaved pioneer weeds leads to prohibitive tending costs. *Tectona grandis* grows well on these sites but it a long term high value, low volume producer. Other doubtful possibilities present are *Anthocephalus cadamba* (A. Rich.) and *Terminalia brassii* (Exell). Attempts to induce artificial regeneration of *Pometia* (J. and G. Forst) species on logged over areas has proved expensive with only poor to moderate success.

E. deglupta is a species with great potential for planting in tropical lowlands. The growth rate in terms of volume are excellent, mean annual increment averaging 450 cu ft/acre/annum (31.5 m³/ha) to age 15 years. However, the proportion of crooked and fluted trees in trial plantations was sufficient to warrant initial selection for stem shape characters. Also, with use for reconstituted products as the probable main product outlet, wood properties were worthy of consideration. This involved a two-

stage selection system; firstly, for growth and form and, secondly, selecting in this population for desirable wood properties. This study has reported several results which may be used as guides for the selection programme.

The wood of 20-year-old *E. deglupta* trees has been shown to have four main components of variation describing 93.5 per cent of the total variance. The variation attributable to each component, and the important wood characters associated with each component are summarized in Table 13.3.

The measurement of only one of the important variables in each of the components could account for 93.5 per cent of the total variation in the wood, each variable making the same proportional contribution as the component in which it appears. It is interesting to note, in wood of this species, fibre length, a variable measured on eucalypt wood by most investigators, has very little significance in describing wood variation when compared with parameters of fibre cross-sectional dimension characteristics.

In general the parameters listed in Table 13.3 are difficult and tedious to measure accurately. As parameters for inclusion in a tree selection programme none were very suitable. Measurement error almost equalled the small between tree differences in all cases. Further it was difficult to obtain a representative sampling position in standing trees, for many of these variables, due to their marked and not always systematic, variation within trees.

Wood density, was found to be well correlated with the first and third components, and hence could effectively represent more than 70 per cent of the total variability in *E. deglupta* wood.

TABLE 13.3 SUMMARY OF COMPONENTS OF WOOD VARIABILITY IN 20-YEAR-OLD TREES

Component Number	1	2	3	4
Percent variation accounted for by the component				
	58.5	18.8	11.9	4.2
Important variables in the component				
	Fibre double wall thickness	Vessel size	Fibre lumen diameter	Fibre length
	Fibre cross-sectional wall area	Proportional vessel volume	Fibre cross-sectional lumen area	Ratio fibre length: fibre diameter
	Fibre cross-sectional area	Proportion by weight crude yield (holocellulosa)		
	Ratio fibre cross-sectional wall area: fibre cross-sectional area	Proportion by weight extractives		
	Ratio fibre double wall thickness: fibre diameter	Proportion by weight lignin		
	Ratio fibre double wall thickness: fibre lumen diameter	Proportional fibre volume		
	Fibre diameter	Proportional ray volume		
	Number of fibres per unit length of radial file on cross-section			
	Number of fibres per unit area of cross-section			
	Ratio fibre cross-sectional lumen area: fibre cross-sectional area			
	Ratio fibre cross-sectional lumen area: fibre cross-sectional wall area			
	Ratio fibre lumen diameter:fibre diameter			

Density varied systematically in the bole and could be representatively sampled with a non-destructive bark to pith sample at ten per cent of total tree height.

Wood density was also a heritable parameter with a narrow sense heritability of 0.44 ± 0.23 and a broad sense heritability of 0.68 ± 0.17 in plants up to two months of age. This, coupled with a phenotypic variation of some 20 per cent between whole tree density averages in 20-year-old trees, marked this property as a suitable parameter for use in a tree selection programme.

This work was shown to have potentially wide application to *E. deglupta* as wood density, determined from seedlings of different provenances, varied little in range and magnitude.

A comparison of a random population of trees with candidate trees, selected in the first stage on the basis of growth and form, indicated that density was little changed by this preselection. A normal population of densities with similar mean and variance remained, however, density represented a slightly greater proportion of the total variance in the candidates than in the random population.

A selection for a narrow density range, slightly above the mean value within the candidates, could be achieved without reducing growth parameters such as breast height diameter or stem volume, as density was shown to be independent of these stem variables in plantation trees up to 20 years old. This will lead to a more uniform product with a greater weight of wood produced per hectare in the same standing volume. This, in turn, will lead to more useable wood material per hectare.

These results were obtained in a species of eucalypt which produces a particularly uniform wood and are in contrast to observations of many other workers on the wood of temperate zone eucalypts. Hence, these results may be atypical for the genus and should not be extrapolated, without investigation, to all fast grown eucalypts. However, the principles, as used in the present investigation, would be the same and there is a need for further detailed studies. Perhaps a pattern would soon emerge whereby certain predictions on wood variability could be made without resorting to further detailed studies. Certainly, if the lowland tropics will be required to produce more wood in fast growing plantations in the future, other genera, such as *Terminalia* for example, should be submitted to detailed examination.

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APPENDIX I

DERIVATION OF THE FORMULA FOR DETERMINING SAMPLE SIZE
WHEN MEASURING VARIABLE MICROGRAPHIC CHARACTERS

For a number of measurements (n) on the one sample having values $x_1, x_2, \dots, x_n$, the mean ($\bar{x}$) is given by the expression

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i$$

The standard deviation (σ) is given by

$$\sigma = \frac{1}{\sqrt{n-1}} \sum_{i=1}^n (x_i - \bar{x})^2$$

and the variance (σ^2) by

$$\sigma^2 = \frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})^2$$

The standard error (S.E.) of the mean is given by

$$\text{S.E.} = \frac{\sigma}{\sqrt{n}}$$

Confidence limits for the mean may be obtained by multiplying the standard error of the mean (S.E.) by the normal deviate (t) for a particular confidence level (e.g., $t = 1.96$ for 95 per cent confidence and sample size of approximately 100 or more individuals).

$$\text{S.E.} \times t \text{ or } \frac{\sigma}{\sqrt{n}} \times t$$

If we require the error to be less than e per cent of the mean, the magnitude of the error with respect to the mean is given by

$$\frac{e}{100} \times \bar{x}$$

If this value is to be within the prescribed confidence interval

$$t \times \frac{\sigma}{\sqrt{n}} = \frac{e}{100} \times \bar{x}$$

thus

$$n = \frac{t \times \sigma \times 100}{\bar{x} \times e}^2$$

but $\frac{\sigma \times 100}{\bar{x}}$ is the expression for the coefficient of variation (σ) and this may be substituted in equation to give

$$n = \left(\frac{\sigma t}{e} \right)^2$$

where n = number of individual measurements required

σ = coefficient of variation of measurements on similar experimental material

t = the normal deviate

e = error per cent of the mean required

If one measures four groups of ($n/4$) fibres at a time and requires the group means to differ by not more than d per cent the expression becomes

$$\frac{n}{4} = \left(\frac{\sigma t}{d} \right)^2$$

where d = per cent difference between group means

other notation as above

or

$$d = \frac{2\sigma t}{\sqrt{n}} \text{ per cent}$$

Any group mean differing from those already obtained by more than this percentage is rejected.

APPENDIX 2 PRINCIPAL COMPONENTS ANALYSIS

The method used here is similar to that of Hotelling (1933). Descriptions of general method may be found in Holzinger and Harman (1941), Thomson (1939), Cooley and Lohnes (1962), Seal (1964) and Kendall (1965). This method has the advantages firstly that the new hypothetical variables (eigen vectors), in terms of which the observed variables are explained, are orthogonal, and secondly, each new variable accounts for as much of the total remaining variance as possible. Theoretically the parameters observed on a large number of wood samples can be explained completely (in the absence of exact linear interdependence between them) in terms of new variables or factors, but where some of the intercorrelations are high, as in this case, most of the combined variance in the data can be explained by a number of new variables which is small in respect to the number of observed variables.

In geometric terms the problem may be depicted briefly as follows by an extension of the explanation of the bivariate correlation scatter diagram given by Sokal and Rohlf (1969, pp 526-543). The data consist of measurements in the form of variations from means of p parameters for each of n samples. Orthogonal axes are set up along which the parameters are scaled and in the resulting space of p dimensions, each sample is represented by a single point. If one expresses the deviations in standard form, then with independent parameters each distributed according to normal law, the points representing the n observations, for fairly large n , take the form of a spherically symmetrical swarm

with density highest at the intersection of the axes, i.e., at the mean values of the parameters and falling off evenly in all directions from the centre. If the parameters are correlated, the spherical distribution will be replaced by an ellipsoidal one. To take an extreme case, if all the parameters were wholly correlated, the swarm of points would be confined to a straight line.

If most, but not all, of the variation of the observations is explainable by a single new variable, the swarm is elongated but not purely linear; and the projection of the n points on to a line forming the core of the point swarm constitute the first component representation of the data. In Hotelling's method, this core is chosen so as to maximise the sum of squares of residues and the resulting line is the first principal axis of the ellipsoidal point swarm. Successive axes may be chosen, to split off components of variance in descending order until the p th operation exhausts the data.

The algebraic procedure is as follows:

Consider a number of measured variables on the samples $x_1, x_2, \dots, x_p$ which may be interdependent and linearly related to each other. A set of new uncorrelated linear variates $\xi_1, \xi_2, \dots, \xi_p$ is desired such that

$$\xi_s = \sum_j \alpha_{js} x_j$$

where x_j = observed variables with $j = 1, 2, \dots, p$

ξ_s = new uncorrelated linear variables with $s = 1, 2, \dots, p$

α = a constant multiplier

The constant α is chosen so that the first new variable ξ_1 has a large a variance as possible. ξ_2 is chosen to be uncorrelated with ξ_1 and also have as large a variance as possible and so on. As the observed variables are normally distributed we may regard the ξ 's as splitting off independent orthogonal component of variance $\lambda_1, \lambda_2, \dots, \lambda_p$ (latent roots or eigen values) from the total variance p . If the original variables are standardised to unit variance, the set of multipliers a_{ij} indicate the relative importance of x_j in ξ_i .

If m new variables are used to express the variation in the system, the hypothesis can be expressed in a group of p equations of the form

$$x_j = \sum_s a_{js} \xi_s$$

where $x_j, j = 1, 2, \dots, p$, are the observed variables and $\xi_s, s = 1, 2, \dots, m$, are the new hypothetical variables. If there is a high degree of correlation in the movement of the variables, one can expect to be able to explain most of the variance of the x_j in terms of a number of the ξ_s which is small compared with the number of observed variables.

In the first component representation of the data, it is desired that each x_j , should be nearly as possible reproduced by $a_{j1}\xi_1$, where the coefficients a_{j1} are constants, one for each observed variable, and ξ_1 is the new variable. The a_{j1} 's and the value of ξ_1 are chosen so that the sum of squares of residues for all variables

$$\sum_j (x_j - a_{j1} \xi_1)^2$$

is a minimum.

Strictly speaking the component is a mathematical artefact however the structure it represents has meaning and so do later theories about the cause of the structure. The fitting of a plausible model to the data is based on experience so the term 'objective' cannot be applied over the whole analysis.

Subjective interpretation is involved to prevent the principle components from becoming just as complex as the original data where it is not uncommon to find most of the eigenvalues significant.

The cumulative proportion of variance (eigen values) removed by each component (d) is given by

$$d_j = \sum_j \frac{\lambda_j}{p}$$

where $j = 1, 2, \dots, m$ and $m \leq p$

p = number of observed variables = total variance

= total of eigen values

APPENDIX 3 FACTOR ANALYSIS

Principal component analysis involved searching the original observations for components in order to reduce the dimensions of variation and also to try and give the components physical meaning. Factor analysis is generally considered to work the other way round; that is, take a model derived by principal component analysis and see if new data agrees with it. This broad distinction between principal component analysis and factor analysis is often blurred in practice, as it is in this study, because both of these operations are being done at the same time to try and understand complicated data structure.

If there are n variables and m factors and linear relationships are assumed, the hypothesis is expressed in a system of n equations of the form

$$x_j = \sum_s a_{js} F_s$$

where x_j , $j = 1, \dots, n$, are the observed variables and the F_s , $s = 1, \dots, m$, are the hypothetical factors.

In factor analysis the new variables F_s ($s = 1, 2, \dots, p$) are obtained in normalized form by dividing the appropriate a_{js} 's in the principal components by analysis to give the factor coefficients F_{js} .

Each of the w equations of the type

$$x_j = f_{j1} F_1 + f_{j2} F_2 + f_{j3} F_3 + \dots + f_{js} F_s$$

is exact if all p factors are included, and is an approximation - a regression equation - if only the first few factors are used.

The relationships

$$F_s = \sum_j f_{js} x_j$$

giving a factor value in terms of the data are exact.

The factor is really a vector of correlation coefficients where the middle sized correlations are still hard to understand. For maximum interpretability of the factor matrix a varimax rotation (Kaiser, 1958, 1959) has been used to impose mathematical conditions beyond the fundamental factor theorem. Thus the factor matrix is uniquely determined by maximising its variance.

Orthogonal rotations are performed on the $p \times m$ factor matrix such that

$$\sum_j [m \sum_i (a_{ij}^2 / h_i^2)^2 - [\sum_i (a_{ij}^2 / h_i^2)]^2]$$

is a maximum, where $i = 1, 2, \dots, p$ variables, $j = 1, 2, \dots, m$ are factors a_{ij} is the multiplier for the i^{th} variable on the j^{th} factor, and h_i^2 is the communality on the i^{th} variable as defined below

$$h_i^2 = \sum_{j=1}^k a_{ij}^2$$

APPENDIX 4 GRAVIMETRIC DENSITY FORMULAE

(a) Density by water immersion method (D_{WI})

I. Calculation of saturated volume

$$W_{SWa} = W_a - W_{WS}$$

$$W_{SW} = U$$

$$U = W_{SWa} - W_w$$

$$\begin{aligned} V_{SW} &= \frac{W_{SWa} - W_W}{\gamma_w} \\ &= \frac{W_a - W_{WS} - W_W}{\gamma_w} \end{aligned}$$

$$V_{wv} = \frac{W_{WS}}{\gamma_w}$$

$$V_t = V_{sw} + V_{wv}$$

$$V_t = \frac{W_a - W_{WS} + W_{WS} - W_W}{\gamma_w}$$

$$\frac{W_a - W_w}{\gamma_w}$$

$$\text{II. Density} = \frac{\text{oven dry weight}}{\text{saturated volume}} = \frac{W_o}{V_t} = \frac{W_o}{\frac{W_a - W_w}{\gamma_w}}$$

where W_{swa} = weight of saturated wall material in air

W_a = total saturated weight in air (water in voids + saturated wall material)

W_{WS} = weight of water in wood voids

V_{SW} = volume of saturated wall material

U = upthrust or apparent loss in weight of material when
Immersed in water

W_w = weight of solids while immersed in water

V_{WV} = volume of water in voids (volume of voids)

V_t = total saturated volume of specimen

W_o = oven dry weight of specimen

(b) Density by maximum moisture method (D_{MM})

i. Volume of wall material

$$= \frac{W_o}{1.53}$$

ii. Volume of voids (= weight of water in the saturated specimen)

$$= W_a - W_o$$

$$\text{iii. Density} = \frac{\text{oven dry weight}}{\text{saturated volume}}$$

$$= \frac{W_o}{(W_a - W_o) + \frac{W_o}{1.53}}$$

where W_o = oven dry weight of wall material

W_a = saturated weight of sample in air

1.53 = density of wood substance (Stamm, 1964)

APPENDIX 5 LIST OF COMPUTER PROGRAMMES

These programmes were written in Fortran IV G for running on the University's IBM Model 360/50 Installation.

1. SCREEN

A programme for screening data under pre-set conditions, taking the sub-set satisfying the conditions and calculating several basic statistics such as mean, median, standard deviation, confidence limits, skewness, kurtosis and the Kolmogorov-Smirnov statistic.

2. WEIGHT CORRE

This programme calculates weighted disc values and weighted whole tree values. A correlation matrix for all combinations of disc values against whole tree values is computed.

3. ARITH CORRE

A similar programme to WEIGHT CORRE except arithmetic averages are used.

4. WEIGHT CORREG

This programme is similar to WEIGHT CORRE except that an optional regression analysis sub-routine is available.

5. ARITH CORREG

This programme is similar to ARITH CORRE except that an optional regression subroutine may be called.

6. FACTO

This programme performs principal component analysis and factor analysis. A varimax rotation is also performed on the factors.

7. CORRE

This programme computes product-moment correlation coefficients between pairs of variables.

Nine other programmes were used for data manipulation. These were specific to the situation for which they were designed and would have no general use. Listings of the programmes are available.

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