FACTORS AFFECTING THE SOIL BINDING CAPACITY OF THE ROOT SYSTEMS OF SOME *POPULUS* AND *SALIX* CLONES

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SUMMARY

The variation in the soil binding capacity of the root systems of six Populus and Salix clones was investigated, and the characteristics of the root systems causing this variation determined.

There were significant differences between clones in soil binding capacity, as measured by the load required to remove the root systems vertically from the soil. This was due more to differences in the morphology of the root systems, particularly the amount of fibrous roots, than to the variation in the tensile strength of individual roots. The variation in the amount of fibrous roots and the tensile strength of individual roots accounted for 71.3% of the variation in the soil binding capacity of the root systems.

There was considerable variation in the morphology of the root systems of trees grown on the same site. The poplar clones generally had more large horizontal roots near the ground surface, with few deep penetrating roots or fibrous roots, while the willows had mostly deeper root systems, and more fibrous roots. An exception was P. yunnanensis, which had both vertical and horizontal roots well developed, and a large number of fibrous roots.

There was more variation within clones than between clones in the tensile strength of individual roots. Intra-clonal variation in anatomy had a significant effect on tensile strength, variation in specific gravity accounting for 79% of the variation in the tensile strength of the stele of P. I488, and variation in microfibril angle accounting for 31% of the variation in fibre wall strength and 19% of the variation in specific tensile strength. In general, tensile strength was negatively correlated, with the diameter of the roots.

There was relatively little difference between clones in the tensile strength of the woody part of the roots, only those of P.I78 being significantly greater in the tensile strength of the stele and specific tensile strength. Differences noticeable in the field were due mainly to variation in the amount of stele present in the roots, which ranged from 25.1% of the cross-sectional area in P. deltoides to 50.3% in S. matsudana. There was some variation between clones in specific gravity and the size

and number of vessels present. Gelatinous fibres were present only in the roots of the willow clones. There was some variation between clones in cellulose and lignin contents. The variation in tensile strength of the stele was correlated with percent fibre wall area and specific gravity, and variation in fibre wall strength and specific tensile strength with cellulose content. There were some significant differences between clones in Young's modulus and strain at failure.

There was considerable seasonal variation in the specific gravity, chemical composition, and tensile strength of the roots. The tensile strength of the stele was highest in the winter months and was correlated with variation in specific gravity. Seasonal variation in fibre wall strength and specific tensile strenth was correlat at a significant level with lignin content and the lignin/cellulose ratio.

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CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Man-induced changes in the vegetation of New Zealand over the last century have resulted in large areas of actively eroding land, both in the steeplands which still retain a form of forest cover, and in large areas of moderate to steep hill country cleared for pastoral use.

By 1941, the seriousness of the problem had been recognised, and Catchment Authorities were constituted, under the auspices of the Soil Conservation and Rivers Control Council, to undertake river and erosion control programs.

Many techniques were used in erosion control work, but most emphasis has been placed on the planting of trees, largely Populus and Salix species.

The planting of trees has proven to have a beneficial effect on counteracting erosion by slumping and gullying, both in retired areas and in those still grazed. It may be assumed that this effect is due primarily to the reinforcing and binding effect of their root systems. The reduction of soil moisture by evapotranspiration is considered to be of secondary importance, as water loss from these deciduous trees is very low in winter, which is the period of maximum soil moisture content and thus maximum instability.

In the past, the selection of poplars and willows for erosion control purposes has been based on the growth and characteristics of the shoot of the tree, while almost nothing was known of the root systems. Variations in morphology and strength of root systems obviously are important factors in the selection of the most suitable species or varieties for soil stabilisation purposes.

Objectives of the study

The primary objective of the study was to investigate the morphology, anatomy, and soil binding capacity of the root systems of a representative number of Populus and Salix clones, in order to determine whether any of the clones were likely to be superior for soil stabilisation purposes, and to determine which characteristics of the root systems were most important for this purpose, as a basis for the selection of improved varieties.

This involved, firstly, the investigation of the morphology and soil binding capacity of the complete root systems of six clones, and the relation between morphology and soil binding capacity. As the soil binding capacity was likely to depend to a considerable extent on the strength of the individual roots comprising the root system, it was also intended to investigate intra-clonal, inter-clonal, and seasonal variation in anatomy, composition, and tensile strength of individual roots, and the relation between these features.

CHAPTER 1 - REVIEW OF LITERATURE

1.1 Use of poplars and willows in erosion control

Poplars and willows are used extensively for the control of erosion in large areas of farmed hill country in New Zealand. They have proven to be the most suitable trees for planting on unstable slopes and gullies under farming conditions. This is due mainly to :

i) Ease of establishment from unrooted poles
ii) Rapid growth rate
iii) Rapid development of an extensive root system
iv) Ability to withstand soil movement

(van Kraayenoord, 1968)

Over the last 20 years, the planting of poplars and willows has increased greatly, and in 1970, the number planted was estimated at 324,000 poles, and 500,000 stakes. (van Kraayenoord, 1971).

Poles are 3-4m. long and 5-10cm. in diameter at the base, while stakes (usually willows) are only 1m. long, and 2-3cm. in diameter. Poles may be established in the presence of stock (wtih suitable protection). (Edwards, 1968).

Poplars and willows are planted in a variety of patterns and situations depending on the type and severity of the erosion problem. On seriously eroded unstable slopes, large numbers of trees may be planted at a close spacing and the whole area retired from grazing. Where erosion is less serious, trees are planted at a wider spacing, and grazing is still practised. They may also be planted alongside streams in pairs or blocks, and around the periphery of unstable gullies. Willows are often used to stabilise actively eroding gullies and protect stream banks.

In most situations, the trees are functioning to prevent soil movement, and this is achieved by the reinforcing action of their root systems.

The use in erosion control of poplars and tree willows grown from unrooted poles in the presence of stock appears to be unique to New Zealand. Rooted trees are used in several countries. e.g. *P. simonii*, *S. matsudana* and *P. yunnanensis* in China (Richardson, 1965), and *P. ciliata* in West Pakistan (Ahmad, 1962). Various species are used in gully bottoms and on spoil dumps in the United States (Maisenhelder, 1960) and in Germany

(Hochhausen, 1964). Willows, both tree and shrub types, are used in revegetation and erosion control work in many countries. e.g. Japan (Endo and Tsuruta, 1968; Higashi, 1962, 1964); Austria (Pruckner, 1967; Schiechtl, 1958); U.S.S.R. (Rokita, 1970; Terebuka, 1971).

1.2 Soil binding capacity of root systems

The capacity of root system to bind the soil and prevent soil movement is related in general, to two factors.

i) The morphology and extent of the root system i.e. the branching pattern, distribution of large and small roots, number of fibrous roots, and the depth and spread of the root systems. According to Dittmer (1948), root hairs also play an important part. Esau (1965) states that the firm attachment of the plant to the soil (which is similar to the soil binding capacity, as far as root morphology is concerned) is dependant on the number of branches, and the number of adventitious roots.

ii) The tensile strength of individual roots, which is related to the anatomy, ultrastructure, and chemical composition of the roots.

The importance attached to each of these factors is determined by the particular environment in which the root system is to function. Thus where a slip plane is present several feet below the surface, as in the tertiary mudstone country of the North Island, the number of deeply penetrating roots and their individual tensile strengths will possibly be the most important factors. Where the whole soil mass is very wet and earth flows are characteristic, the number of fibrous roots will possibly be the most important factor.

Very little research has been published on the ability of tree root systems to bind the soil. The paucity of work in this field is surprising, as large areas of land throughout the world are afforested specifically for this purpose.

Higashi (1964) has determined the "soil binding power" of four year old Salix sachalinensis trees under nursery conditions, by measuring the maximum load required to remove the root system vertically from the soil.

Loads required varied from 132-600 kg.

An exponential relationship was derived between the size of the root system and load required.

Similar types of studies have been carried out with herbaceous plants such as maize and rice (Miyasaka, 1970) but with the alternative aim of measuring the soil holding capacity as an aid in the selection of plants resistant to wind throw and lodging.

Endo and Tsuruta (1968) investigated the effect of tree roots on the shearing and tensile strength of soil. For shearing strength, they measured the load required to move a block of soil with or without roots across a shear plane.

Shearing strength of the soil increased considerably with the bulk weight of roots. The tensile strength of the soil was measured using necked moulds containing soil with or without vegetation, and was shown to increase proportionately with the weight of roots. The binding effect of grass roots was much less than that of tree roots, due to their concentration near the ground surface.

1.3 Root systems of poplars and willows

Root systems of plants in general have been studied relatively little in comparison with above ground features, and this lack of information is doubtless related to the difficulty in studying underground structures, some of which may be quite extensive. The root systems of poplars and willows are no exception, and there is relatively little work reported in the literature on this topic.

1.3.1 Morphology of root systems

Before briefly reviewing the few studies that have been carried out with regard to morphology of the root systems of poplars and willows, it should be emphasized that the form of the root system of a tree is integrally related to the site where the tree is growing. This relationship appears to be considerably more important than the effect of the environment on the

morphology of the above ground parts of the tree.

The depth to which the roots penetrate illustrates the effect of the environment on the morphology of the root system. There are two schools of thought regarding the relative importance of genotype and environment with regard to root system morphology. This is discussed by Sutton (1969), who used spruce as an example of the variability in root system morphology that can occur over a range of sites. He quotes many workers who consider the root system of spruce to be under rigid genetic control, being characteristically shallow and plate like. He refers to others, however, who have investigated the variability more carefully, over a range of sites, and have observed both shallow and deep rooted trees. The conclusion follows that the spruces are not characteristically shallow rooted, but this observation arises from their ability to occupy sites where the root system is restricted to surface layers, thus emphasising the influence of the environment.

Bibelreither (1966), in discussing the relation of root systems to soil characteristics, thinks that the widely used terms "shallow rooted" and "deep rooted" are misleading, and given unrestricted development, all trees reach about the same depth with their roots.

Fraser (1966), investigated the morphology of the root systems of a number of species, and found the development of the main roots was largely determined by the soil type, and no major differences occurred between species on the same soil type.

However, Kozlowski (1971) says there are many examples of woody plants that have an inherent capacity for unusually deep root penetration, and gives a number of examples. Zimmerman and Brown (1971), agree that many woody plants possess a characteristic pattern of root development, even if grown under different environmental conditions, and that inherent differences in the pattern of root development are especially noticeable during seedling growth.

Root systems often became modified in later years by enviromental influences such as overall nutrition (Bibelreither, 1960; Zimmerman and Brown, 1971).

It appears then that in general, the morphology of the root system is under genetic control, but can be greatly influenced by the environment.

This means that the results of any investigation of root system morphology must be related to the site where the tree is growing, and any generalisations treated with caution.

The root systems of trees grown from poles or cuttings will possibly be quite different in morphology from those grown from seed. Cuttings and poles normally produce a number of adventitious roots, while seedlings usually produce only a single tap root in the initial stage of root development.

Little work has been reported on the morphology of the root systems of the varieties investigated in this study, but some related varieties are mentioned, together with general features of the species.

Kostler et al (1968) review studies on the root systems of poplars conducted by several German authors. Most work has been done on poplars by Joachim (1953, 1957) who studied the root systems of 12 poplar clones growing on different sites in North Germany. The horizonal spread of the root systems appeared to be controlled by soil characteristics and the tree spacing. He found that on poor soils the poplars tended to have a more extensive root system than on better soils. On poor soils the spread was many times the width of the crown, while on fertile soils, it was only slightly greater than the crown width. Where a humus rich top soil was present, the roots preferred to stay in this layer. The depth of the root system was very dependant on the ground water level and soil conditions. For example, a 40 year old P. robusta formed many sinker roots which originated in strong horizontal roots, and formed dense "brushes" immediately above the 50cm. deep water table. Deeper going roots were killed by the water table. In flood plains, with young, loamy soils, poplars developed intensive and deep heart root systems.

Hoffman (1966) compared the root systems of 2 year old P. robusta and P. trichocarpa, growing in experimental containers. P. trichocarpa developed fewer roots, but had more thicker roots in deeper soil layers than P. robusta.

Joachim (1957) observed that P. trichocarpa developed a very wide and flat, horizontal root system, and a less extensive vertical root system.

Both Joachim (1953) and Hoffman (1966) call the euramericana poplars intensive rooting, and the trichocarpa type poplars extensive rooting.

Kostler et al (1968) state that in general poplars can in no way be called flat rooting, and there are inherent differences in their rooting patterns. They are only flat rooting on sites with high water tables or soils with a high calcium content.

Joachim found that the area between close spaced trees contained relatively few roots near the surface, with most roots going downwards. With trees planted at a wide spacing, many roots were found in the humus rich topsoil.

Dagenbach (1971) studied the root systems of several poplar varieties growing on different sites, and found P. Oxford had a deeper root system on all sites. Androscoggin, I 214 and Jacometti 786 all had strong root systems 100cm. or more deep. That of P. robusta was less deep, and P. regenerata shallowest.

The root systems of four poplar varieties growing on the same site were investigated by Visy (1965). The varieties were recognisably distinctive. P. marilandica was shallow rooting, with roots mainly in the humus layers. The roots of P. serotina occupied moister zones, those of P. robusta preferred the drier layers near the surface, and P. I 214 was the only variety with roots almost equally distributed in all horizons.

Steubling (1960) found P. alba had a deep and penetrating root system.

The lateral extent of the root system is also affected by soil physical properties and moisture, and Koslowski (1971) gives an example of lateral roots of P. deltoides extending for more than 60 metres.

Ortmann (1958) studied the root systems of young willows grown from seed and cuttings, and reported genetic differences between species and hybrids. All plants showed a heart root system and he found there were horizontal "feeder" roots in the well aerated superficial layers, and deeper going "drinkers" and supporting roots.

Higashi (1964) investigated the growth and distribution of the roots of three Salix varieties, finding S. viminalis had the largest spread, followed by S. sachalinensis. Schiechtl (1958) describes the root systems of several willow varieties and their suitability for revegetation and erosion control work. Morphology of the root systems depended largely on the site, although the ratio of root volume to shoot volume showed considerable

differences between species e.g. Salix incana, 1.8, S. purpurea 1.5, S. triandra, 0.4.

A preliminary investigation of several of the poplar and willow varieties used in the present study showed marked differences in rooting depth between the varieties growing on the same site. (Hathaway, 1970). Poles were planted .75 metres deep into a sandy loam soil, and the root systems examined after 2 years by sluicing away the soil. The poplar clones I-488 and I-78 showed considerable differences in root morphology. Both clones developed the largest and longest roots in the top 30cm. below ground level. However, I-78 developed fewer roots, but these were larger and deeper penetrating roots than in I-488, which formed many shorter, more fibrous roots in a zone 30 to 50cm. below ground level. Root systems of S. matsudana and S. Booth developed more deeply penetrating root systems than the poplars, reaching 2-2.5 metres below ground level. The roots of the willows appeared to have considerably greater tensile strength than those of the poplars, although no measurements were made.

It can be seen from the above studies that considerable genetic variation in root system morphology exists in the Populus and Salix genera, even though site conditions may have a large influence.

1.3.2 Anatomy of roots

Relatively little work has been reported on the anatomy of rootwood of poplars and willows. The secondary xylem of woody roots in general is similar to that of stems, although minor differences may occur. (Esau, 1965; Fahn, 1967). According to Esau, roots generally have a smaller number of fibres, larger vessels of more uniform size, and a higher ratio of bark to wood. The fibres are generally shorter in roots than stems (Panshin and de Zeeuw, 1970). Patel (1965) compared the anatomy of rootwood with that of stemwood of several hardwood species, including P. canadensis (P. x euramericana). Growth rings were less distinct, parenchyma more abundant, and rays occasionally biseriate in the roots, while in the stem, vessels were smallest and more numerous, rays uniseriate, radial pore multiples more frequent, fibres narrower, and gelatinous fibres were occasionally found. He suggests that some of these differences may be due to the existence of a longer juvenile period in the root than in the stem.

Gelatinous fibres were not found in the roots of any of the species, but in an earlier study (Patel, 1964) they were present in the roots of P. tremuloides, where they were abundant on all radii irrespective of the orientation of the organ with respect to gravity. Gelatinous fibres in stemwood are normally associated with eccentric development.

Ruggeri (1963) examined the anatomy of roots of one year old trees of several P. x euramericana clones, and found that few differences were evident between clones. Only P. I 214 differed to any extent, due to the constant presence of a pith. There were some differences in the amount of cortex in the roots, P. I 45/51 having the least (54.1%) and P. I 214 the most (63.3%).

1.3.3 Tensile strength of individual roots

Very little work has been reported in the literature specifically on the tensile strength of tree roots.

Turmania (1965) investigated the tensile strength of roots of five tree species, in order to calculate the "soil stabilisation value" of the vegetation in the Moscow area. The species selected were Populus deltoides, Betula pendula, Tilia cordata, Quercus robur, and Picea abies. Roots were taken from trees growing under similar ecological conditions and of the same age. Only roots from 0-30cm. below the ground surface were sampled. About 400 tests were carried out, on roots of varying diameters. Roots with diameters less than 1cm, were broken complete, while with larger roots, samples .3 x .5cm. in cross-section were tested.
The following results were obtained :

1) The load required to break the stele together with the cortex was very close to that required to break the stele alone. Failure began in the cortex, which often broke completely at a load much less than that required to break the stele. e.g. a poplar root of diameter 5.2mm. lost its cortex at a load of 28 kg. while the stele broke at 41 kg. He concluded from a number of such tests, that the cortex played little part in contributing to the tensile strength of the root.

2) In thin roots (0.7-1.5cm.) he found a marked dependence of the strength of the root on the diameter, smaller roots sustaining higher stresses. Turmania attributed this to the "scale effect", seen also in the strength

of crystalline substances. He thinks that in roots, this is caused by the crystalline nature of cellulose.

In roots greater than 1.5cm. in diameter, the "scale effect" disappeared and he thinks this may be due to the greater lignification of these roots.

3) The tensile strength values of the five species studied were as follows :

	mean of all samples	mean of samples in diam. class 0.2 - 0.7cm
poplar	3.91 kg/mm^2	2.35
birch	3.82	2.23
linden	2.65	2.05
oak	3.24	2.25
spruce	2.78	1.89

The strength of roots in winter was 1½ - 2 times that of roots in summer, and this was correlated with differences in moisture content. The moisture content of summer samples was from 1½ - 2 times that of winter samples. The strength of trunk wood was from 2 - 4 times greater than that of root wood of the same species.

Schiechtl (1958) investigated the tensile strength of some tree and herbaceous plants in relation to their suitability for erosion control work. He mentions a number of species with "strong" roots, but the only detailed test results given were :

Populus nigra	.493 to 1.20 kg/mm^2
Artemisia campestris	.91 to 2.64 kg/mm^2
Medicago sativa	2.54 to 6.65 kg/mm^2

Stiny (1947) gives the tensile strength of roots of a number of herbaceous species.

e.g.	Agropyrum repens	.72 - 2.53 kg/mm^2
	Trifolium pratense	1.09 - 2.85 kg/mm^2
	Atriplex patulum	.93 - 3.06 kg/mm^2

1.4 Factors affecting the tensile strength of roots

1.4.1 Diameter of the root

As mentioned above, Turmania found that in thin roots (0.7-1.5cm. in diameter), the smaller the diameter of the root, the greater the tensile strength (in terms of load per unit area).

The same relationship also appears to be present when the results of Stiny (1947) are studied. A large number of roots of herbaceous species were tested, and in most cases, particularly in roots between 0.1 and 0.5cm. in diameter, smaller roots withstood greater tensile stresses.

Schiechtl (1958) concludes the reverse relationship, but as he only tested a small number of roots of three species only, his conclusion may be doubtful.

In most materials, there is a strong dependence of strength on size (Mark, 1967). This effect has been seen in tensile tests on wood (Sumiya and Sugihana, 1957). A small specimen of wood could sustain applied stresses substantially greater than those a large specimen from the same tree could resist, other things being equal. The dependence of strength on size is very pronounced in small crystalline filaments (Brenner, 1965). Timoshenko (1956) has proposed a formula relating the strength to the size of geometrically similar specimens.

Why roots of the relatively large size of 0.7 to 1.5cm. in diameter, compared with crystalline filaments, should exhibit this dependence of strength on diameter is not clear. It is possibly related to anatomical features present in younger, smaller roots, that are not present in larger roots.

1.4.2 Relative amounts of stele and cortex

The results of Turmania (1967) show that the ultimate tensile strength of a root depends almost entirely on the strength of the stele, and this seems quite reasonable, as the cortex is composed mainly of parenchyma, with some schlerenchyma (Esau, 1965). As differences have been shown to occur in the proportions of cortex and stele (Ruggeri, 1963), the relative amounts of these tissues will be an important factor in contributing to the overall strength of the root.

1.4.3 Tensile strength of the stele

Anatomically, rootwood is very similar to stemwood (see section 1.3.2) and factors affecting the strength of stemwood are likely to have a similar effect in rootwood. No reference could be found in the literature to factors specifically affecting the tensile strength of rootwood.

The tensile strength of stemwood has been the subject of a considerable amount of research over the last decade, and many factors have been shown to be involved. These include specific gravity, fibre dimensions, microfibril angle, percent fibre wall area, size and number of vessels, chemical composition and moisture content.

Ultimately, it is the fibre cell wall which bears the load when a wood sample is subject to tensile stress, and consequently the strength of a particular wood sample will depend on two major factors.

a) the amount of cell wall material present in the sample and,
b) the strength of the cell wall itself.

a) Amount of cell wall material present

Specific gravity is an approximate measure of the amount of cell wall material present, but can be affected by other substances not present in the cell wall such as extractives and starch, and variation in the specific gravity of the cell wall itself.

The specific gravity of the cell wall substance is thought to be relatively constant, at about 1.53 (Jane, 1970). Specific gravity has been correlated with various strength parameters on many occasions (e.g. Clarke, 1937; Desch, 1968; Jane, 1970), and is probably the most widely used parameter indicating the overall strength of wood samples.

A number of workers have studied the relation of tensile strength to specific gravity. Wellwood (1962) found the most important factor affecting tensile strength of small parallel to the grain sections of Western Hemlock and Douglas fir was specific gravity ($r = .90$).

Kellog and Ifju (1962), in a study relating the physical characteristics of 20 tree species to differences in the properties of wood in tension parallel to the grain found that specific gravity was the single

most important factor, and was linearly related to both tensile strength and modulus of elasticity.

Van Vliet (1959), working with Douglas fir, found that 33.1% of the variation in ultimate tensile strength was accounted for by differences in specific gravity, but he concluded that other variables may affect tensile strength more than specific gravity does.

Hill (1949), in a study of tensile strength variation in Balsa, established a fairly high correlation between tensile strength and specific gravity.

Specific gravity is, in itself, determined by anatomical characteristics such as the percent cell wall area, cell lumen, or vessels, and fibre wall thickness. It is therefore clear that it will be more highly correlated with strength than any of these anatomical measurements individually. However, such factors have been correlated with tensile strength. e.g. in the work by Hill (1949) 86% of the variation in tensile strength was accounted for by differences in specific gravity, with an improvement to 89% where the additional factors of percent fibre wall area and percent earlywood pore area were added.

The effect of specific gravity may be modified by other anatomical or chemical characteristics. e.g. Wilson and Ifju (1965) found specific gravity explained up to 92% of the variability in strength properties in Douglas fir. However, they also found that although earlywood showed a constant specific gravity, strength properties increased progressively across it, and this was due to differences in cellulose content and tracheid length. Desch (1968) gives examples of wood of the same specific gravity exhibiting large ranges in strength values.

The amount of cell wall material present is related to the time of the year when the cells were formed, springwood having larger fibres and vessels, with thin walls, and summerwood having smaller fibres with thick walls. The vessels in summerwood may also be much reduced in size in ring-porous species (Jane, 1970). Thus Wellwood (1962) found that the position in the annual ring where a sample was taken from was highly correlated with specific gravity ($r = 0.84$). The tensile strength of summer wood was 2-4 times greater than that of springwood.

b) Strength of the cell wall

The basis of the tensile strength of cell walls is partly anatomical, partly chemical and partly due to their molecular arrangement. The present understanding of the ultrastructure and composition of the woody cell wall is given by Harada (1965); Muhlethaler (1965); Preston (1952); Roelofson (1959); Wardrop (1951, 1962, 1964) and Wardrop and Harada (1965). Only a brief outline need be given here.

The wall of a typical fibre consists of a thin primary wall, (P), inside of which are a thin outer layer (S_1), broad central layer (S_2), and thin inner layer (S_3), comprising the secondary wall. The S_3 layer adjoins the cell lumen. Primary and secondary wall layers consist of long chain cellulose molecules, variously arranged, and interspersed and encrusted with hemicelluloses, lignin, and other substances. The orientation of the cellulose chains has been shown to be the same as that of the microfibrils (Wardrop and Davies, 1964), which varies from layer to layer. In the primary wall, they are irregularly arranged in a loose network; in the S_1 and S_3, at large angles to the long axis of the cells and in the S_2 at a much narrower angle to the long axis of the cell. Fibres are bonded together by inter-cellular substances consisting mainly of pectopolyuronides and lignin in the middel lamella between cells. Various models of a typical fibre have been proposed, all showing the above structure in general, but differing slightly in further details (e.g. Wardrop and Bland, 1959; Harada, 1965).

The relation between the structure of cell walls and their mechanical behaviour was studied over 70 years ago by Schwender (1894), and since then, many workers have investigated the problem. Due to the complexity of the arrangement of the cell wall, no simple relationships can be obtained, and many factors have been shown to be involved. Tensile strength of fibre walls has been highly correlated with cellulose content, microfibril angle, fibre length, moisture content, and to a lesser extent, size, and lignin and hemicellulose contents.

(i) Cellulose content

Cellulose is the principal structural component of wood, and the work of Klauditz (1952, 1957) indicates that the tensile strength of wood depends mostly on cellulose content. Many other authors have found very

high correlations between cellulose content and tensile strength (e.g. Barefoot (1965); Ifju and Kennedy (1962); Kennedy and Javorsky (1960); Wellwood (1962). Ifju (1964) investigated the effect of cellulose chain length on the tensile strength of wood, by systematic depolymerisation of cellulose, and concluded that the mechanical properties of wood depend mostly on cellulose content. The cellulose molecule in wood is an oriented, long-chain, unbranched polymer which is packed into a crystalline lattice over much if not all of its length (Mark, 1967). The chains in the lattice are strongly attracted laterally by secondary bonds, which are important in determining the elastic and strength properties of wood.

(ii) Microfibril angle

Almost every property of wood or fibres that has been studied in connection with the microfibril angles shows high correlation with these angles (Mark, 1967). Usually the broad central layer (S_2) is considered exclusively in such studies.

Tests relating the S_2 microfibril angle to tensile strength almost invariably show high correlation. (Berkley, 1939; Betrabet and Iyengan, 1964; Frey-Wyssling, 1959; Garland, 1939; Ifju and Kennedy, 1962; Meredith, 1956; Preston, 1960; Wardrop, 1951; and Wellwood, 1962). The smaller the angle the S_2 microfibrils make with the fibre axis, the greater is the tensile strength, stiffness, and resistance to creep.

(iii) Fibre length

Fibre or tracheid length has also been high correlated with tensile strength. (Ifju and Kennedy, 1962; Wardrop, 1951; Wellwood, 1962), longer fibres showing higher strength values.

Wellwood's (1962) results also showed a high correlation between fibre length and microfibril angle. Mark (1967) discusses the relation between cell length and microfibril angle, and proposes the formula

$$L = a + b \cot \theta$$ where a,b = constants, L = cell length, θ = S_2 winding angle

(iv) Moisture content and lignin content

Moisture content has been shown to influence the strength of wood by many workers. (e.g. Klauditz et al, 1947; Wardrop and Addo-ashong, 1963; Zodorina and Cernova, 1965). Wood and other fibres show decreased moduli and increased elongation when tested under conditions of increased moisture content. The effect is only noticeable when the moisture content is below the fibre saturation point (25-30%), (Desch, 1968).

Moisture content appears to interact with lignin in affecting strength. Klauditz et al (1947) found the removal of lignin increased dry strengths, but wet strengths decreased by almost 80%. He concluded that lignin protects hydrophilic substances that can bear load when dry but not when wet, and that "the special biological function of lignin is to endow wood with the necessary strength when wet".

Lignin is deposited in association with the matrix substances in the inter-cellular layer and inter-microfibrillar spaces of the wall (Wardrop, 1965). It is more heavily concentrated in the region of the middle lamella and primary wall, and is deposited in lesser concentrations throughout the secondary wall (Albersheim, 1965; Bailey, 1936, a,b; Mark, 1967; Meier, 1964).

Meier (1964) states that 90% of the lignin is localised in the region of the middle lamella and primary wall, but Mark (1967) disagrees with this.

Lignin has commonly been regarded as bulking and rigidising material. It is deposited throughout the wall to a large extent after the structural carbohydrate framework has been formed by the living cell (Freudenberg, 1964; Kratzl, 1965), and the deposition continues until the death of the cell and continues in the inter-cellular layer while deposition takes place in the secondary wall (Wardrop, 1965). Lignification of the wall may be associated with an increase in wall thickness (Wardrop, 1965).

Lignin content has more often been related to compressive strength, and cellulose content to tensile strength (Desch, 1968; Kollmann, 1967). Runger and Klauditz (1953), investigating the relationship between the chemical composition of poplar stemwood, and its strength properties found this to be the case. Dadswell and Wardrop (1955) suggest that the principal function of lignin is to act as a reinforcement of the cellulose framework.

Grozdits and Ifju (1969) found that an increase in lignification of eastern hemlock tracheids during development did not result in any increase in tensile strength.

(v) Hemicelluloses

Leopold and McIntosh (1961) found a relationship between tensile strength and xylan containing hemicelluloses and suggest that binding between microfibrils is also important.

(iv) Seasonal variation in chemical composition

It has been shown on several occasions that springwood and summerwood differ in chemical composition, as this presumably affects the strength of the cell walls of these tissues.

Wise (1944) investigated the composition of springwood and summerwood of a number of American hardwoods and softwoods. The springwood contained a greater proportion of lignin than the summerwood, and he thought this was due to the greater proportion of middle lamella in springwood cell walls. In general, the cellulose content of summerwood was greater than that of the springwood.

Wardrop (1965) found the Cress and Bevan cellulose content of springwood of P. radiata to be 45%, while that of summerwood was 57.7%.

Allsopp and Misra (1940) found new wood had higher lignin and lower cellulose contents than ordinary sapwood in elm and ash.

Stewart et al (1953), working on Eucalyptus regnans found lignin increased from 12% in developing sapwood to 25% in heartwood.

Phillips (1954) noticed that earlywood of English ash was less lignified than the remainder of the ring.

As lignification follows cellulose deposition (Freudenberg, 1964; Kratzl, 1965) it would follow that the lignin content of older tissues would be greater. However, the very high proportion of lignin in the middle lamella and primary wall appears to modify this, causing variation in the results obtained. The sequence of lignification will affect lignin content. According

to Stewart et al (1953) lignification commences in the developing sapwood and is completed in the mature sapwood. Northcote (1958) also found that lignification was not complete till the sapwood was mature.

Schneidwind (1966) found differences in tensile strength between earlywood and latewood, but this was due to differences in microfibril angle within the S_2 layer, and the proportion of this layer in the total cross section.

1.5 Stress/strain relationships and extensibility of roots

There does not appear to be any reference in the literature to work on stress/strain relationships and extensibility of tree roots, although Turmania (1967) did measure the lengths of the roots he tested before and after breaking, thus giving a measure of plastic deformation.

From a soil stabilisation viewpoint, the elasticity and extensibility of roots may be an important factor in determining a tree's suitability for this purpose.

The modulus of elasticity is obtained from a stress/strain diagram, and is defined as the strain divided by the stress at the proportional limit. The appearance of a proportional limit in a load-deformation test is evidence that the sample possesses a visco-elastic rather than simple elastic nature. Its mechanical properties are time dependent. The value of the proportional limit relative to maximum strenth will be dependent on the elapsed time of the load-deformation test (Jayne, 1959). A test conducted over a period of a few seconds may exhibit linearity to failure, whereas a test conducted over a period of several hours will probably show curvilinearity from zero to failure.

At normal strain rates, such as the 1% elongation per minute used by Jayne (1959), and Kellogg and Ifju (1962), small wood samples characteristically show a proportional limit. The stress/strain diagram, is however, essentially linear, with only a slight fall off of the curve beyond the proportional limit.

Wet samples show a decreased modulus of elasticity and greater elongation than dry samples (Jayne, 1959).

1.6 Measuring the tensile strength of roots and small wood samples

Turmania (1965) does not describe in detail the method used for testing woody roots, other than 20cm samples were used, which were broken in a tensile testing instrument of a particular type.

Grips have been described by McGowan (1968) for testing larger samples of timber in tension, but are not suitable for small roots.

Most work on the tensile properties of wood has been done on small sections, having the advantage of being easier to handle and also of being more representative of a particular cell type. Most test specimens have been of the necked down type, ranging from 20 microns in thickness (Runger and Klauditz, 1953) to 80 microns (Ifju and Kennedy, 1962; Schniewind, 1959; Wardrop, 1951; Wellwood, 1962). Mark (1967) used test specimens 20-25 microns thick, containing a single cell type. Rectangular section samples have been used (e.g. Ifju, 1964), and these appear to give 2-12% higher strength values than necked down specimens (Ifju et al, 1965; Wellwood et al, 1965).

Tensile properties have also been investigated by glueing small samples of wood approximately 2 x 2mm. in cross-section into larger blocks of wood or metal, and inserting a small pin through the block and the sample to give additional holding power (Meylan, B.A. pers. comm.).

Tensile tests are usually carried out on an Instron or similar testing instrument (e.g. Jayne, 1959; Kennedy and Ifju, 1962; Wellwood, 1962), whereby a constant rate of strain may be applied, and the load automatically recorded via a load cell and moving chart. The crosshead speed selected depends on the sample size. Mark (1967) used a speed of .05mm/min., giving about 6.6% elongation per minute with his particular samples. Hartler et al (1963) have determined the optimum strain rate to be of the order of 50% elongation per minute. Very slow speeds (.005-.01mm/min.) have usually been used with small samples (Ifju, 1964; Kennedy and Ifju, 1962) and individual fibres (Jayne, 1959).

1.7 The measurement of anatomical characteristics

1.7.1 Specific gravity

The specific gravity of wood is defined as the weight of the oven dry wood divided by the weight of a volume of water equal to the volume of wood.

The volume may be that of the wood when oven dry, green or at some intermediate moisture condition. The problem when dealing with very small samples of wood is the accurate determination of the volume. Smith (1954, 1955) has reviewed the methods available for small samples, and basically, there are three approaches.

(i) Weight - volume method

If the metric system is used, then 1gm. is the weight of 1cc. of water and the formula for specific gravity becomes :

$$\text{SG (fresh)} = \frac{\text{ovendry weight (gms)}}{\text{green volume (ccs)}}$$

or

$$\text{SG (ovendry)} = \frac{\text{ovendry weight}}{\text{ovendry volume}}$$

There are several methods available for obtaining the volume of small wood samples, such as the mercury - displacement, water-immersion, and photometric methods. The volume determinations are usually the least accurate and most difficult to obtain, and these are discussed further by Smith.

(ii) Standard water-immersion method

Vintilla (1939) described a technique for obtaining the specific gravity of small samples ranging in volume from 200 to 1000 cubic mm. by the standard water immersion method. This method requires the determination of three weights for each sample, from which the specific gravity is calculated: the soaked weight; the weight held submerged in water; and the ovendry weight.

(iii) Maximum moisture content method

Smith (1954) describes a method developed by Keylwerth (1954) based on the specific gravity and the maximum moisture content of wood. This method has the advantage of requiring only two weight determinations: the weight of the completely water saturated sample, and its ovendry weight. From these two weights, together with a constant that represents the density of cell wall substance, the specific gravity is calculated.

$$\text{SG} = \frac{1}{\frac{\text{M max - M od}}{\text{M od}} \quad \frac{1}{\text{density of cell wall substance}}}$$

M max - wt. of water saturated sample

M od - wt. of ovendry sample

A comparison of this method with the standard water immersion method, by Smith (1955), gave a mean difference of less than 1%, and she concluded that from the standpoint of the technique and time involved, the maximum moisture content method is far superior.

1.7.2. Cell type percentages and cell wall area

Two methods are available, depending on the measure required.

(i) One procedure involves taking photomicrographs or making drawings using a camera lucida. The area required may be planimetered, or cut out and weighed. Alternatively, the image may be projected onto a screen and the area required planimetered.

These methods have been used for the determination of the area and volume occupied by various cell elements such as rays (Myer, 1922), and for the determination of cell wall areas of single wood fibres (Jayne, 1960; Leopold, 1966) and small sections of wood (Mark, 1967).

(ii) The sampling of microtome sections at selected points has been applied to the measurement of the relative proportions of various cell elements (Mark, 1967) and cell wall areas (Ladell, 1959; Tsoumis, 1964).

This method involves taking point samples on transverse sections, and recording the cell type or lumen etc. on which they fall. The proportion of points falling on the cell type is considered to give the percentage of that cell type in the area sampled.

The sampling points are determined by grid intersections, the grid either being placed in random positions over the section or at regular intervals. Tsoumis (1964), found there was little difference between the two methods. Mark (1967), found that placing the grid in alternate positions across the section gave satisfactory results. It is clear that the size of the grid, the size of the section, and the accuracy required will determine the number and spacing of grids necessary.

1.7.3 Fibre dimensions

The maceration of wood samples to enable individual fibres to be measured may be achieved by several methods.

(i) Nitric acid and chromic acid

Treat with equal parts of 10% nitric acid and 10% aqueous chromic acid, for 24 hours at 35°C. (Johansen, 1940).

(ii) Acetic acid and sodium chlorite

This method is described by Spearin and Isenberg (1947), and modifications by Winton and Dickey, (1968). Fibre separation is achieved by treating the sample with a mixture of 1:6 wt./vol. sodium chlorite and acetic acid (1M) at 90°C for 7-8 hours.

(iii) Hydrogen peroxide and glacial acetic acid

Samples may be macerated by treating with a 1:1 mixture of glacial acetic acid and 30% hydrogen peroxide at 50°C for 48 hours. This method has been used successfully for Populus sp. by Farmer and Wilcox (1968).

As a large number of samples may be treated simultaneously with stable reagents, this method appears the most satisfactory.

Fibres may be stained with a number of stains, e.g. Congo red (Winton and Dickey, 1968), methyl fast blue (Johansen, 1940). Slides are prepared in the normal manner, either with or without a coverslip.

The measurement of fibre dimensions may be carried out using an automatic recorder, (as described by Winton and Dickey, 1968), or directly, using an eyepiece micrometer.

1.7.4 Microfibril angle

A number of methods have been used to determine the mean microfibril angle in cell walls.

(i) Measurement of pit aperture angles, cell wall striations, and mechanically induced cracks

These features have been used in the determination of microfibril angle by a number of workers (e.g. Bailey, 1938; Kellogg and Ifju, 1962; Wardrop and Davies, 1964). According to the latter authors, the angle of these striations etc. is the same as the angle of the microfibrils

in the S_2 layer. They are often more easily distinguished under polarised light.

(ii) Deposition of crystals in the cell wall

This method was originally described by Bailey and Vestal (1937), whereby crystals of iodine are induced to form in the "elongated porosities" of the cellulose matrix. It is assumed in using this method that the iodine crystals are alligned parallel to the microfibrils in the S_2 layer. Bailey and Berkley (1942), have pointed out that this technique can also show the orientation of microfibrils in the other two layers (S_1 and S_3) of the secondary wall. Meylan (1967), reported that the method failed most frequently when samples had small microfibril angles.

(iii) The study of X-ray diagrams

X-ray diffraction has been used by Preston (1952), Frey-Wyssling (1959), and Meylan (1967), amongst others. Meylan describes the method as follows. An x-ray beam is directed along the direction of the rays and perpendicular to the long axis of the tracheids and fibres. The x-ray diagram is obtained photographically and the microfibril angle may be obtained from the interpretation of the diagram. The method is fairly quick, involving little observer time, compared with the large number of measurements necessary with all the other methods. The main disadvantage is that whereas the other methods may be supposed to give a direct measure of angle, the x-ray diagram must be interpreted. Various empirical methods for interpreting the diagram have been proposed, all considering the distribution of intensity around the most intense arc of the diagram.

Meylan (1967), compared the method with several other methods, and obtained a highly linear relationship.

(iv) Polarising microscopy

The major extinction position of the wall has been used for some time in the measurement of microfibril angle (Frey-Wyssling, 1959; Preston, 1952; Wardrop and Preston, 1951).

The fibres must be sectioned in such a way that a single wall may be examined.

(v) Electron microscopy

This has been used to measure microfibril angle directly (Frey-Wyssling, 1959; Roelofsen, 1959), although electron micrographs often show many overlapping microfibrils orientated over a range of angles.

(vi) Recently, the planes of enzymatic hydrolysis by soft-rot fungi have been used to determine microfibril angle (Cowling, 1965).

1.8. Determining the chemical composition of wood

In investigating the effect of chemical composition on strength properties, it is primarily the cell wall components, cellulose, hemicelluloses, and lignin that are of interest. However, it may be necessary to determine other substances such as extractives and starch which, although not situated in the cell wall, can affect the relative contents of the major components when investigating varietal and seasonal variation.

Browning (1967), has comprehensively reviewed methods of determining the chemical composition of wood, and the following general statements, unless otherwise indicated, are from his review. The quantitative determination of wood composition cannot be achieved by any simple scheme, as the major components exist as inter-penetrating systems of high polymers, which without chemical modification, are insoluble in all common solvents.

The extractives that are soluble in water and in neutral organic solvents can be removed fairly easily. For the investigation of the polysaccharide and lignin components, "extractive free" wood is generally accepted as a satisfactory starting material.

The major part of the lignin cannot be removed in unchanged form by any solvent. Lignin preparations are obtained as insoluble residues after hydrolysis with strong mineral acids.

1.8.1. Polysaccharides

The determination of the polysaccharide portion of the wood is accomplished either by the removal of lignin, or the hydrolysis of the cellulose and hemicelluloses to simple sugars, the amount of which may then be determined. The process of delignification requires the use of strong oxiding agents or acidic or basic solutions at elevated temperatures, and these treatments produce some

oxidation and hydrolysis of cellulose and other polysaccharides. When delignification is carried out under conditions such that essentially all the polysaccharides are retained in the preparation, the product is called holocellulose. Treatment of the holocellulose with strong aqueous alkaline solutions dissolves the major portion of the hemicelluloses and leaves a residue of alpha-cellulose, composed mainly of cellulose. The hemicellulose portion of the polysaccharides consists of many different polymers, which vary in the kind and amount of sugar units present.

The standard method for holocellulose is probably the sodium chlorite procedure developed by Wise et al (1946). Various modifications have been used e.g. the chlorine ethanolamine and peracetic acid procedure (Leopold, 1961). Another classical method is that of Cross and Bevan (1911), whereby lignin is chlorinated with chlorine gas or chlorine water, and oxidation products formed are removed with sodium sulphite. A modification for small samples has recently been used by Watson (1962).

Mark (1967), considers the Cross and Bevan type method to be a superior procedure when studying strength properties, due to the higher content of alpha-cellulose contained in C & B cellulose than in chlorite holocellulose. The method also seems to avoid the danger of degrading some cellulose to a soluble state, as might occur in alpha-cellulose determination. It also eliminates those hemicellulose fractions not closely associated with the microfibrils.

Hydrolysis of the polysaccharides to simple sugars can be carried out progressively, most of the hemicellulose fraction being hydrolysed by weak mineral acids, while the resistant hemicelluloses and cellulose are only hydrolysed by strong mineral acids (Wenzl, 1970). The cellulose is converted quantitatively into glucose, by splitting the beta-glucosidic linkage by the addition of water. Hemicelluloses, however, give a mixture of sugars and sugar derivatives (Wenzl, 1970). The acid to wood ratio appears to be critical in the hydrolytic methods. Sakai (1965), concludes that an effective concentration must be between 60% and 75% for the hydrolysis of cellulose. It is also necessary that a uniform distribution of the highly concentrated acid is achieved, and the material must be extensively reduced in size and mixed thoroughly.

1.8.2. Lignin

The quantitative determination of lignin in wood presents difficulties due to the indefinite concept of lignin, differences in the chemical nature of materials accompanying lignin, and the fact that chemical reactions of lignin

affect the validity of lignin determinations (Browning, 1967). Brauns and Brauns (1960), agree with this and state that no definite formula for lignin is known, so it appears that no definition of lignin in a quantitative sense can be given.

Despite these problems, several methods have been devised that are suitable for comparitive purposes. The generally most useful methods have been based on hydrolysis and solution of the polysaccharides with strong mineral acids, leaving a residue which after washing and drying, is weighed as lignin. Extraneous material which might remain insoluble along with the lignin must be removed before the acid treatment. The methods are summarised by Pearl (1967).

(i) The sulphuric acid method

The use of sulphuric acid for the determination of lignin was first applied by Klason (1923), (cited by Pearl, 1967). The original method has been modified extensively by various workers, but the lignin isolated with this acid is usually referred to as "Klason" lignin. In general, the hydrolysis of the polysaccharides is accomplished effectively by an initial treatment with strong sulphuric acid (68-72%) until the partially hydrolysed polysaccharides first formed are no longer precipitated upon dilution. The acid mixture is then diluted with water and boiled to complete the hydrolysis. Suitable pre-extractions are necessary to remove extraneous materials that otherwise would appear with the lignin.

The determination is affected by acid concentration, time of treatment and temperature. If these factors are too great, humification of the carbohydrates may lead to the formation of partially insoluble degradation products that appear with the lignin. If the concentration is too small, time too short, or temperature too low, the polysaccharides may be incompletely hydrolysed and remain in part with the residue of lignin. The optimum concentration appears to be in the range 72-74% for most woods (Browning, 1967).

(ii) Modified sulphuric acid methods

Various modifications have been proposed e.g. Jayme et al (1958), have obtained rapid hydrolysis by application of a mixture of sulphuric acid and phosphoric acid.

(iii) Methods have also been used utilising hydrochloric or hydrofluoric acids (e.g. Willstatter & Zechmeister, 1913).

(iv) Many workers have observed that the filtrate from wood treated with strong acids contains substances that possess many of the properties which characterise lignin, although their nature is not clear, and have been termed soluble lignin. The filtrates of hardwoods often show u.v absorption at 210-280 m p, which is characteristic of soluble lignin preparations. Hardwoods may contain from 1-4% soluble lignin. It has been found that the lignin of Eucalyptus regnans was acid soluble to the extent of 16% of the Klason lignin (Browning, 1967).

1.8.3. Extractives

Extractives include those compounds soluble in organic solvents, (e.g. resins, fatty acids, waxes) or water (inorganic salts, sugar, water soluble carbohydrates, some phenolic substances). Some of the materials soluble in water are more or less soluble in many organic solvents, and vice versa.

Extractive free wood is prepared by extracting the sample successively with ethanol-benzene and 95% ethanol for 4 hours each, in a Soxhlet extractor, then with 3 or 4 portions of distilled water at 100^{o}C (Browning, 1967).

1.8.4. Starch

Starch is often found in the sapwood of angiosperms, usually in the form of simple granules up to 10-12 microns in diameter. According to Browning (1967), starch contents in wood from 0.5% to 5% have been reported, but the amount is subject to wide seasonal fluctuations, and there is much uncertainty in the methods of determination.

A method for the quantitative determination of starch in plant tissues has been developed by Nielson and Gleason (1945), whereby the starch is dispersed by perchloric acid and the iodine complex determined by spectrophotometry. This method was later modified by Puchner et al (1948), to allow for species differences in the ratio of amylose to amylopectin.

The method has been applied to the determination of starch in wood (Humphreys and Kelley, 1961).

CHAPTER 2 - MATERIALS AND METHODS

2.1. Species used in the study

Four Populus and two Salix clones were used in the study. These were chosen to be representative of sections of the genera, and also to be representative of the commonly used poplar and willow species planted for erosion control in N.Z.

A description of the characteristics and classification of the Populus and Salix clones used in the investigation is provided in Appendix 1 as a background to the selection of the six clones used.

Species and clones used were :

1. Populus x euramericana cv. I-78
2. P. x euramericana cv. I-488
3. P. yunnanensis
4. P. deltoides cv. A60/129
5. Salix matsudana
6. S. purpurea cv. Booth.

At this point, the terminology used regarding species, varieties, and clones should be clarified. As almost all members of the Populus and Salix genera are propogated vegetatively, and in New Zealand exist often as the result of a single introduction, many species are represented by only one clone. However, some species and hybrds are present as a number of clones, and to avoid confusion, the species, varieties, or clones used in this study are referred to as clones, even if they are the only form present.

Thus inter-clonal variation refers to the variation present between the clones used in this study, and not to variation between clones of the same species.

Intra-clonal variation refers to variation between roots of the same tree or trees of the same clone.

2.2. Procedures

2.2.1. Study of the morphology and soil binding capacity of the complete root systems

Fifteen cuttings of each of the six clones were planted in a randomised block layout (4 replications, 6 blocks, 1 cutting per plot), in August, 1971. At the end of the first seasons growth, the trees were 3-4m. high. Because some cuttings did not strike, only the 10 largest trees of each clone were used, and were removed from the ground in July, 1972. The load required to pull the trees from the ground was measured using the procedure outlined in Section 2.3.1. The trees were removed in July, as soil moisture during this time of the year was at a high level, thus simulating as closely as possible actual conditions when soil movement is most likely to occur. Three trees of each clone with the most typical root systems were selected for morphological investigation. The general morphology of the root systems was recorded photographically. The following quantitative data were obtained :

1) The size and number of roots originating on the upper and lower 10cm. of the cuttings.
2) The air-dry weight of fibrous roots, which were defined as all secondary or higher order roots less than 1mm. in diameter.
3) The air-dry weight of the total roots and shoots separately (as the trees were deciduous, the shoot weight did not include the weight of the leaves).
4) The diameter of the stele of all roots greater than 1mm. in diameter, at the point where the roots had broken.

Root/shoot ratios were calculated for the three selected trees per clone, and were defined as :

$$\frac{\text{air-dry weight of roots}}{\text{air-dry weight of shoots (without leaves)}}$$

The root/shoot ratios were less than the true values, as the extremities of many roots remained in the ground. However, the roots of all clones appeared to break at about the same diameter, and the ratios were adequate for the purpose of comparison. The small size of the root extremities remaining in the soil meant that the ratios were only slightly lower than their true values.

In order to investigate the effect of variation in the morphology of the root systems on soil binding capacity, it was necessary to remove the effect

of the size of the root system. This was achieved by using a "root system strength index" being defined as :

$$\frac{\text{maximum load attained when removing root system (kg)}}{\text{air-dry weight of roots (g)}}$$

The effect of fibrous roots on soil binding capacity was investigated by comparing the measured load required to remove the root system with the predicted load required. The predicted load was obtained by calculating the total cross-sectional area of the steles over all the breaks for roots greater than 1mm. in diameter, and the mean diameter of the steles at the breaks. By multiplying the total cross sectional area of the steles by the tensile strength of roots of this diameter typical of the clone, the load required to break all the roots together was estimated. The typical tensile strengths of roots of the required diameter for each clone were obtained from tensile tests of individual roots (see section 3.3.3). The difference between the predicted load and the actual load required to remove the root system was theoretically due to the effect of the roots less than 1mm. in diameter, and to friction between the soil particles and the region of the roots proximal to the breaking points.

2.2.2. Study of intra-clonal variation in the anatomy and tensile strength of individual roots

For the study of intra-clonal and inter-clonal variation, 20 trees of each clone were grown from cuttings in a randomised block layout, with 5 trees of each clone per block. The cuttings were planted during August, 1971.

For the study of intra-clonal variation, roots of one clone only (P. I 488) were used. 40 roots (10 from each block) were collected in June, 1972, after the trees had been growing for one season. Those collected were mainly lateral roots of 4-8 mm. diaeter, showing minimum taper, and from a depth of 0-30cm. below the soil surface. From these roots, 30 were selected with diameters of the steles evenly spread over a range of 2-4 mm. Test samples were prepared and broken in the testing instrument, and the load at failure recorded (see section 2.3.2). Some test samples broke unevenly due to slight kinks in the roots, and several pulled out of the blocks used for gripping the ends of the roots. 20 samples giving satisfactory test results were selected for the calculation of the tensile strength of the stele, fibre wall strength, and specific tensile strength (see section 2.3.4).

The following anatomical data were determined for each sample. (as described in sections 2.3.7-11).

1) specific gravity
2) percent fibre wall area (of total cross-sectional area)
3) percent vessel area (of total cross-sectional area)
4) mean vessel diameter
5) percent parenchyma and rays (of total cross-sectional area)
6) mean fibre length
7) mean fibre width
8) S_2 microfibril angle

The chemical composition of the individual samples was not determined.

2.2.3. Study of inter-clonal variation in anatomy, chemical composition, tensile strength, and stress/strain behaviour of individual roots

The results of the study of intra-clonal variation showed it was necessary to use at least 20 roots of each clone to show significant differences in tensile strength between clones (see section 3.3).

Thus roots of each clone were collected as in the intra-clonal investigation, and 30 test samples of each prepared. These were broken in the testing instrument, and 20 samples selected for the calculation of the tensile strength of the stele, fibre wall strength, and specific tensile strength. For these calculations it was necessary to determine the cross-sectional area of the test sample, fibre wall area, and specific gravity (sections 2.3.3, 2.3.7, 2.3.11).

It was not possible in the time available to determine quantitatively all the anatomical features of all the test samples of each clone. For example, to measure microfibril angle alone for all the samples of the six clones would have required three weeks of microscope work.

To enable comparisons of anatomical characteristics to be made between clones, one sample of each clone with a value for the tensile strength of the stele typical of the clone was selected. The selection of samples with 'typical' tensile strength values was complicated by the fact that tensile strength was significantly correlated with the diameter of the test sample. It was thus necessary to use samples of the same diameter for the comparison, 3mm. being selected as an average value. Typical samples were selected by

calculating the adjusted means of the tensile strength of the stele by a covariance analysis, whereby the regression of strength on the diameter of the stele was taken into account. The 3mm. diameter sample with a value for the tensile strength of the stele closest to the adjusted mean for the clone was used for the comparison.

The following anatomical data were determined.

1) percent vessel area (of total cross-sectional area)
2) mean vessel diameter
3) percent parenchyma and rays (of total cross-sectional area)
4) mean fibre length
5) mean fibre width
6) microfibril angle

Specific gravity and percent fibre wall area were determined previously for all samples tested.

Inter-clonal variation in chemical composition was determined by analysing bulked samples of all the roots of each clone that were used in the tensile tests. (see section 2.3.12).

Equal volumes of each root were used, irrespective of diameter and specific gravity. The cellulose content was determined by hydrolysis, and also by the method of Cross and Bevan (see section 2.3.12).

For the examination of stress/strain behaviour, load/extension curves were produced for four of the above samples, covering the range of diameters, for each of the 6 clones. Young's modulus, ultimate strain, and the ratio of ultimate stress to ultimate strain were obtained from the stress/strain diagrams (see section 2.4.3).

2.2.4. Study of seasonal variation in specific gravity, chemical composition, and tensile strength of individual roots

For the study of seasonal variation, two clones, P. I 488 and S. matsudana were used. As with the other trees used in the study, cuttings were planted in August, 1971. However, trees for this part of the study were grown in single rows. Root samples were collected (as in section 2.3.2) at monthly intervals, from February, 1972 to January, 1973, representing the period of growth of the trees from near the end of the first growing season to near the end of the second. It is pointed out that as roots of a given size range were sampled (4-8mm. in diameter), the samples did not represent roots of different ages, but roots that had developed over a particular

period during the year.

Each month 20 roots per clone were collected from trees in different positions in the rows, test samples prepared and broken in the testing instrument. Ten samples giving satisfactory test results and a range of diameters were selected, and used for the determination of cross-sectional area, fibre wall area, and specific gravity. Tensile strength of the stele, fibre wall strength, and specific tensile strength were calculated.

The chemical composition of each monthly samples was determined, carbohydrates being determined by hydrolysis.

2.3. Techniques

The numerous techniques used in carrying out the above investigations will be described together in this section, as several of the investigations involved the use of the same techniques.

2.3.1. Measurement of soil binding capacity

To obtain an estimation of soil binding capacity, the maximum load reached when the trees were pulled vertically from the ground was measured. The trees were pulled from the ground using a block and tackle supported by a tripod, as shown in fig. 1. A dynonometer, which was capable of measuring loads of up to 4000 kg, and could be read with an accuracy of ±10 kg, was linked between the block and the tripod. The tackle was attached to the base of the stem of each tree with a chain, after removing the bark to obtain a better grip. The load was increased at a constant rate, and the maximum load reached as the root system was removed recorded.

2.3.2. Tensile testing of individual roots

It was found when removing complete root systems that the roots, in general broke where their diameter was between approximately 4 and 8 mm. It appeared that a "critical zone" existed in the root, proximal to which the root was too strong to be broken by tension, and distal to which was capable of resisting being pulled through the soil, due to the greater number of fibrous roots. Thus roots for tensile testing were selected from this range.

No satisfactory method for testing the roots in the fresh conditions could be devised. The major problem was that of gripping the ends of a root in such a way that the root was not damaged, or weakened, but still able to withstand the load required to break the root without slipping.

Fig. 1 Equipment used for measuring the load required to remove the root systems from the soil

If the roots were of uniform diameter for some distance, the method used in testing textile fibres could be used, whereby the fibre is wound round a drum several times, utilising its own friction to sustain the load. However, the roots were not of uniform diameter for any distance, tapering from the base to the tip, and they were also of insufficient length to wind around a drum and this method could not be used.

It was thus necessary to use a method developed for the tensile testing of small wood samples, whereby the root was glued into small wooden blocks which could then be clamped in the testing instrument without damaging the root itself. This necessitated removal of the cortex, and drying the roots, in order to glue them satisfactorily into the blocks, and then resaturating them before testing.

The removal of the cortex was considered not to reduce the ultimate tensile strength. When roots were broken in the field, the cortex always broke before the stele, and often broke much closer to the base of the root than did the stele, which then pulled out of the remaining cortex.

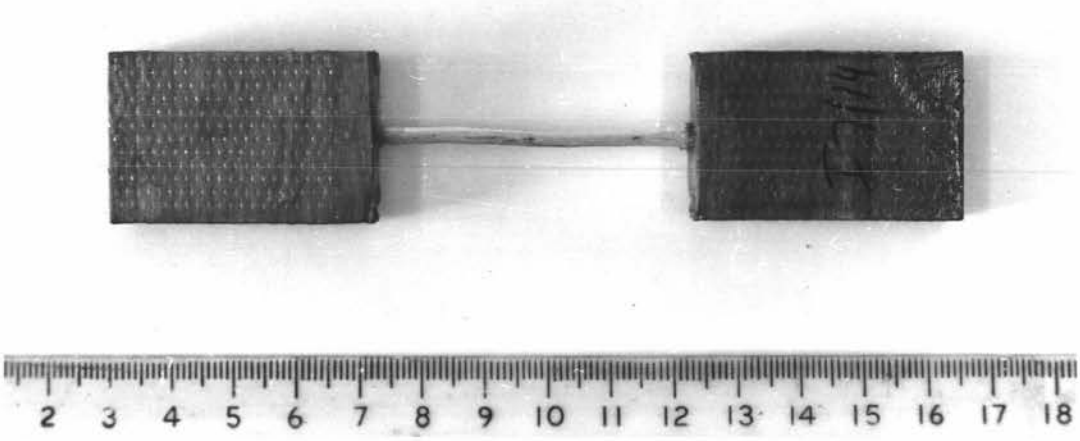
The drying of the roots before testing may be criticised on the basis that some irreversible change in the cell wall structure may have occurred, which had an effect on the tensile strength. However, after resaturating, the roots regained their flexibility and elasticity, and appeared to be in a similar condition to that before drying. Microscopic examination of the roots after drying and resaturating did not show any checks or distortion. Most of the fibres and vessels of the stele would have been dead (see section 1.3.2); and thus the drying would not have affected them physiologically.

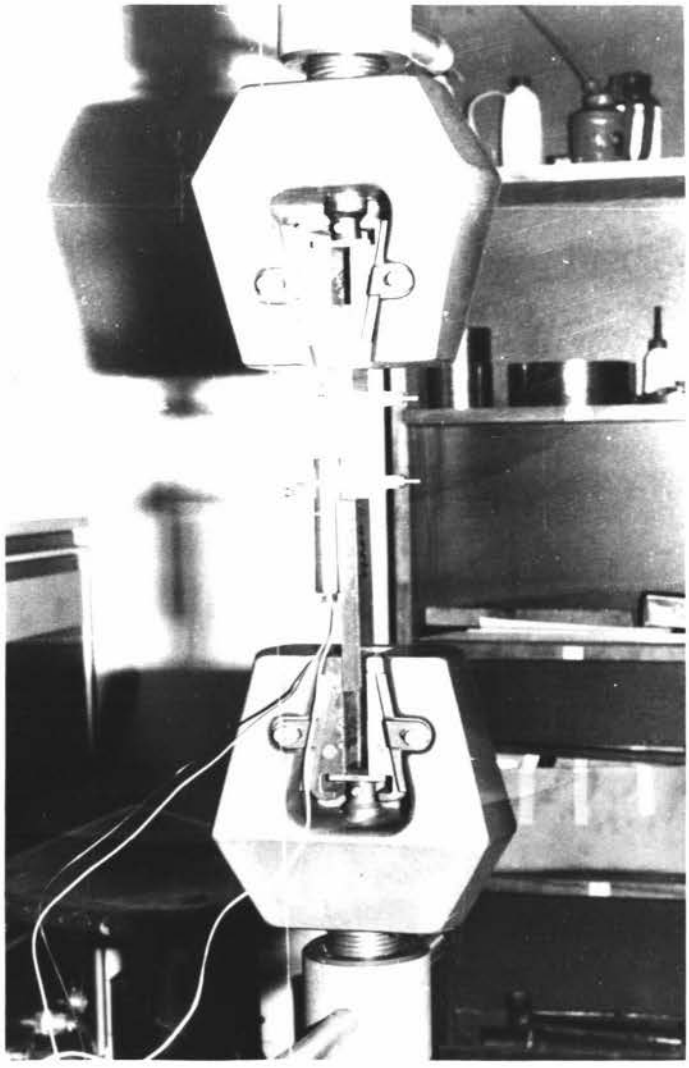
The test samples were prepared as follows. After collection of the roots from the field, the cortex was removed and the samples air dried. Lengths of roots with steles 2-4mm. in diameter, and as uniform a diameter as possible, were selected, and small wooden blocks 3 x 4 x 0.8cm, glued to the ends using Araldite adhesive. The roots were glued into closely fitting holes drilled across the grain of the blocks. The length of the test samples between the blocks was 5cm. (see fig. 2).

In order to simulate the roots in the fresh condition as closely as possible, it was necessary that the moisture content of the test samples be above fibre saturation point. This is the moisture content at which theoretically the cell walls are saturated, but there is no water in the lumens of the cells. In practice, the fibre saturation point is at 25-30%

Fig. 2 A typical tensile specimen

Fig. 3 Method of gripping the sample in the tensile testing instrument. The transducer used for determining stress/strain relationships is also shown.


2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18



moisture content, depending on the wood (Panshin and de Zeeuw, 1970). Above the fibre saturation point, the moisture content of the wood samples has little effect on strength properties (Jane, 1970).

A pilot investigation (see appendix 3) showed that a soaking period of 1 hour before testing resulted in a moisture content of the samples of 50-60%. Thus the samples were soaked for this period, to ensure that the moisture content was above fibre saturation point right through.

Preliminary tests of samples prepared in the above manner resulted in many of the roots being pulled out of the blocks without breaking. To achieve satisfactory results, it was necessary to seal the blocks before soaking, and this was done by applying two coats of polyurethane varnish.

Tensile tests were carried out on a floor model Instron universal testing instrument. A 500 kg load cell was used, the load being recorded continuously on a moving chart. Using this load cell, a full scale range on the chart could be selected from 10 to 500 kg, depending on the expected load required to break a particular test specimen. The range could be increased during a test.

To determine whether the rate of extension of the sample during testing had any effect on the tensile strength, an investigation was carried out using two crosshead speeds - 20 cm/min. and .05 cm/min. (see appendix 4) As this showed paired samples tested at each speed not to differ significantly in tensile strength, an intermediate crosshead speed of 1cm/min. was selected as a satisfactory rate. This resulted in a sample elongation rate of 20% per minute, and failure occurred in most samples after 1-2 minutes of extension.

A chart speed of 2cm/min. was used. Provided no slippage occurred within the blocks or at the grips, the distance travelled by the chart before failure occurred would be proportional to the actual extension of the 5cm. test sample, and the shape of the plot drawn on the chart would be equivalent to a stress/strain diagram. However, it appeared from the chart record and observations during testing that some slippage and strain was occurring within the blocks. For the accurate determination of stress/strain relationships, it was necessary to utilise a separate extensometer attached directly to the test specimen. No extensometer was readily available that would measure the degree of extension that was occurring.

To overcome this, an extensometer was constructed using a Phillips PR 9314A/10 transducer with a range of ± 10mm. (see fig. 3). When used with a 4cm. test sample, this arrangement was capable of measuring strains of up to 25% with the core of the transducer moving only in a positive direction.

The output from this type of transducer was not acceptable to the X-Y Servo Chart Drive system of the Instron and a separate X-Y recorder was used. The signal from the strain transducer was recorded on the X-axis, and the signal from the load cell of the Instron on the Y-axis of the recorder.

2.3.3. Determination of cross-sectional area of test samples

Due to the irregular shape of many of the roots in cross-section, it was necessary to use transverse sections for the determination of cross-sectional area. Sections were prepared as described below (see 2.3.5.).

The area was determined using a Reichert visopan microscope with the image appearing on a ground glass screen 20cm. in diameter. For this purpose it was fitted with a grid of 5 x 5mm. squares. A 4 x objective was used, resulting in a magnification on the screen of 50 x. The number of grid intersections which fell on the image of the transverse section was counted, and as each grid intersection represented the mid-point of a square of known area, the actual area could be calculated.

Some distortion of the image was evident using this type of microscope, a known distance at the objective appearing slightly greater in the centre of the screen than at the edges. To allow for this distortion a number of concentric circles were drawn on the grid, and the number of grid intersections within each circle converted to an area by a factor appropriate to that part of the screen. The cross-sectional areas of the section within each circle were then summed to give the total cross-sectional area of the root.

The mean diameter was calculated from the cross-sectional area.

2.3.4. Calculation of tensile strength

i) Tensile strength of the stele was defined as :

$$\frac{\text{load at failure (kg)}}{\text{total cross-sectional area of the stele (mm}^2\text{)}}$$

ii) As the tensile strength of wood depends mostly on the strength of the fibre walls, an estimate of the strength of the fibre walls was obtained from the formula.

$$\text{fibre wall strength} = \frac{\text{load at failure (kg)}}{\text{cross-sectional area of fibre walls (mm}^2\text{)}}$$

This estimate was below the true value, due to the proportion of the load that was brone by the vessel and parenchyma walls. However, as these components have relatively thin walls and are considerably weaker the error involved was probably quite minor.

iii) Specific tensile strength was used to remove the effect of differences in specific gravity on tensile strength, and was defined as :

$$\frac{\text{tensile strength of the stele (kg/mm}^2\text{)}}{\text{specific gravity}}$$

As specific gravity is a measure of the amount of cell wall substance present, specific tensile strength is also a measure of the strength of the cell walls.

However, it is based on all the cell wall material present, whether from load bearing cells or otherwise.

2.3.5. Preparation of sections for anatomical study

After tensile testing, a small section of each sample was taken immediately adjacent to the break, for the preparation of transverse sections. Sections were cut from unembedded material 15 microns thick on a sliding microtome, as close to the break as possible. They were stained in 1% safranin, dehydrated in alcohol, and mounted in Canada Balsam.

A common criticism of many quantitative anatomical studies is that a certain amount of distortion of the cells is caused by the mounting medium. To minimise any such distortion in the sections to be used for the determination of cross-sectional area, one thicker section (30-40 microns) was cut at the same time as the thinner sections, and was used for this purpose. Little distortion was apparent with the thin sections, and as all measurement on these sections were as percentages, any slight distortion would be of little consequence.

2.3.6 Photomicrographs

All photomicrographs were taken using a Leitz microscope fitted with planochromatic lenses, and attached camera, with ordinary light. The film used was Ilford FP4.

2.3.7 Determination of fibre wall area

A grid was also used for the determination of fibre wall area. The principle of the grid method is based on the assumption that the number of grid intersections which fall on the particular cell type or structure, divided by the total number of grid intersections, is an estimate of the proportion of the particular cell type or structure present in the area covered by the grid.

For the measurement of fibre wall area, a 10 x 10 grid was used on the screen of a Reichert Visopan microscope, the lines being 1.3cm apart. A 63 x objective was used, giving a magnification on the screen of 800 x. The grid was placed in 50 positions evenly spaced over the image of the section (by moving the slide under the objective), and a record made of the nunber of grid intersections per grid position which fell on fibre walls, thus involving 5000 determinations per section.

Whenever a grid intersection fell on the boundary between a fibre wall and the cell lumen, which was not often, the point was assigned alternately to fibre wall or lumen.

The average of the number of grid inter-sections per grid which fell on the fibre walls was an estimate of the fibre wall area as a percentage of the total cross-sectional area, and from this an estimate of the actual fibre wall area was calculated.

The error involved when this method was used was 3% (see Appendix 2).

2.3.8 Determination of proportions of other cell types

The areas of the cross-section occupied by parenchyma and rays, and vessels, were determined by the same method. It was not necessary to use such a high magnification for these cell types, as the range of values resulting from the grid determinations was much less than those for the fibre wall area determinations. This meant that the same accuracy could

be achieved with only 2500 determinations (see appendix 2).

The 40 x objective was used, giving a magnification of 500 x.

2.3.9. Determination of fibre dimensions

Macerations were prepared by treating small pieces of the test samples with a mixture of 1:1 sodium peroxide and glacial acetic acid at 50°C in an oven for 3 days. Each sample was then washed twice with water, reduced to fibres by mild shaking, and stained with a few grains of cresyl fast violet.

Fresh slides were prepared for each series of fibre measurements.

a) Fibre length

100 fibres were measured for each test sample. This number was necessary as there was a considerable range in fibre lengths. All unbroken fibres >350µ were measured. Measurements were made to the nearest 1mm. on the screen of the microscope, representing a fibre distance of 7.58µ. at a magnification of 50 x. The error involved was less than 2% (appendix 2).

b) Fibre diameter

Fibre diameter was measured in a similar manner but as the range of diameters was considerably less than the range of fibre lengths, it was only necessary to measure 50 fibres to achieve the same accurancy. (see appendix 2). A magnification of 800 x was used. The error involved was less than 1.5%.

2.3.10. Measurement of microfibril angle

The macerated fibres showed in nearly all cases easily seen slit pits and helical fractures, which could be used for the measurement of microfibril angle. The angle of the pits or fractures of 50 fibres was measured at the mid-point of each fibre. A magnification of 500 x was used, and the angle measured to the nearest degree with a protractor on the screen of the microscope.

2.3.11. Determination of specific gravity

The maximum moisture content technique (see section 1.7.1) was used. A section of root with a volume of approximately 15mm^3 was taken

from each test sample immediately adjacent to the break, trimmed of any rough edges with a scalpel, and soaked in distilled water under intermittent vacuum for 10 days. The distilled water was changed twice during this period.

Each of the saturated samples were weighed to the nearest .0001gm in tared vials, removing any excess moisture by wiping with a damp piece of muslin before weighing. They were then dried in an oven at 105°C for 12 hours, removed from the oven, and placed immediately in a dessicator to cool. After 10 minutes they were reweighed to obtain the oven-dry weight.

Calculation

$$\text{Specific gravity} = \frac{1}{\frac{Mm-Mo}{Mo} + \frac{1}{Gso}}$$

where Mm = wt of saturated sample.
Mo = oven dry wt.
Gso = density of wood substance = 1.53

The method assumes that the density of wood substances remains constant from sample to sample.

Later in the study, it was found that the roots contained a considerable quantity of starch during the winter months (up to 25% of the dry wt.) and that highly elevated specific gravity determinations were resulting.

These were corrected by subtracting the weight of starch estimated to be present in the sample from the saturated and oven dry weights, and recalculating the specific gravity.

The amount of starch estimated to be present in the sample was derived by using the percentage of starch determined for the whole group of samples (see section 2.3.12), and multiplying by the oven-dry weight. Slight errors have resulted due to varying amounts of starch present in roots of the same group of samples. However, starch analyses of individual roots were not considered due to the time involved in analysising such a large number of samples.

2.3.12 Determination of chemical composition

A representative sample of each group of roots to be investigated was obtained by collecting, from each sample, a section adjacent to that being used for the tensile test specimen. Equal volumes of root material from each sample were obtained, irrespective of the diamter of the roots. It was not possible to use the actual test sample after it had been broken, as insufficient material remained after samples had been taken for specific gravity determinations and sectioning. However, it is unlikely that adjacent sections of the same root would differ markedly in composition. The bulked sample was reduced to small segments, and ground in a mill to pass a 40 mesh sieve.

Extractives were determined by the loss in weight after successive extractions with 1:2 ethanol benzene and 95% ethanol in a soxhlet extraction apparatus, and washing with hot water.

Hemicelluloses were determined collectively by hydrolysis of extractive free material to simple sugars with 5% H_2SO_4, and the amount of sugar determined by Nelson's (1944) colorimetric method. The determinations were affected by the presence of starch, which was also hydrolysed to simple sugars, and it was necessary to determine starch separately (see below). The hemicellulose content was then estimated by subtraction.

Cellulose Two methods were used for the determination of cellulose.

a) By hydrolysis : (see Section 1.8.1). The residue remaining after the hemicellulose fraction had been removed was hydrolysed to glucose by the action of 72% H_2SO_4, and the amount of glucose determined by Nelson's method.

b) By delignification : "Cross and Bevan" cellulose was determined by the semi-micro method of Watson (1962). Lignin was chlorinated with chlorine water, the reaction stopped by the addition of sulphurous acid, and the chlorinated lignin removed by hot sodium sulphite. Several cycles were necessary (usually 5) to completely remove the lignin and the end point was indicated by the absence of a red colouration on the addition of sodium sulphite.

Lignin was determined gravimetrically by the loss of weight upon ashing the residue after the extractive, hemicellulose, and cellulose fractions were removed.

The hydrolysis method had the advantage that the same sample could be extracted successively with different solvents for the determination of the major constituents, thus minimizing the amount of root material required, and the time involved.

Starch A combination of the methods of Pucher et al (1948) and Humphreys and Kelly (1960) was found to give satisfactory results.

The material was ground as finely as possible with the available grinder, and the starch dispersed by the action of perchloric acid. At the same time, the suspension of wood material and perchloric acid was macerated with a close fitting glass mortar and pestle to obtain a more complete dispersal of the starch. After centrifuging, the starch was determined by starch-iodine spectrophotometry.

Detailed procedures of all the above analytical methods are given in Appendix 5.

2.4. Experimental design and analysis

Trees used in the investigation of soil binding capacity and inter- and intra-clonal variation in tensile strength of roots were grown in randomised block designs as described in the relevant sections. Those used for the investigation of seasonal variation were grown in rows, and at each sampling date, roots were collected from different positions in the rows.

Simple two-way analyses of variance were used in the study of inter-clonal variation in the morphology and soil binding capacity of the root systems.

Inter-clonal and seasonal variation in the tensile strength of individual roots was analysed by covariance methods, due to the significant correlation between tensile strength and the diameter of the stele of the roots. The relation between anatomical characteristics, chemical composition, and tensile strength provided problems in analysis as none of the variables could be controlled and selected for by the investigator. This meant that statistically efficient designs could not be used, and the analyses were restricted to simple correlations and regressions.

The relation between intra-clonal variation in anatomy and tensile strength of roots of P. I 488 was analysed by multiple regressions. The

standardised partial regression coefficients were calculated and indicated the importance of each anatomical characteristic in predicting tensile strength. Analyses of variance of the multiple regressions indicated the significance of the contribution of the anatomical variables. The proportion of the variance in tensile strength due to anatomical characteristics used in the regressions was calculated.

CHAPTER 3

RESULTS

The morphology of the root systems, and the anatomy, composition, and tensile strength of individual roots will be given first, and then the relationship of these factors with soil binding capacity discussed.

3.1. Morphology of the root systems

The ten trees of each clone were removed from the ground (as described in section 2.3.1), and the morphology of the root systems investigated using the three trees of each clone with root systems most typical of the clone. There were distinct differences in morphology between clones, but only minor differences within clones, and these were mainly due to differences in the size of the trees.

The general characteristics of a representative root system of each clone are shown in fig 4. The root systems of the willows differed in a number of respects to those of the poplars although P. yunnanensis showed characteristics of both genera. Differences between clones were apparent in the following.

(i) Position on the cutting where the majority of roots originated

All the clones had a majority of roots originating from the base of the cutting. However, S. matsudana, P. I488, and P. yunnanensis also had a considerable number of roots originating from the upper part of the cutting, while the other clones had relatively few. These roots were mainly small and fibrous in S. matsudana, but quite large in P. yunnanensis. The mean number of roots originating from the upper and lower regions of the cutting and their size classes, for the three trees selected as being typical of each clone, is given in fig 5.

(ii) Depth and spread of the root systems

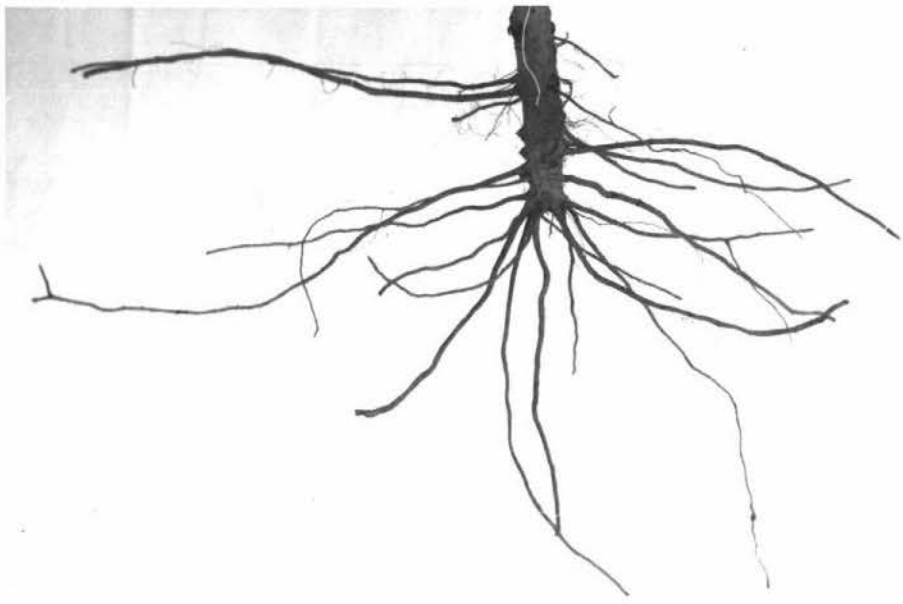
The willows characteristically had deeper root systems than the poplars. Both S. matsudana and S. Booth had most large roots originating at the base of the cutting, and these were oriented downwards at an angle of approximately 45^{o}. Most large roots of the poplars were restricted to the surface layers. P. yunnanensis was an exception, and had both vertical

Fig. 4 Morphology of the root systems

Top : P. I-78

Centre : P. I-488

Bottom : P. deltoides



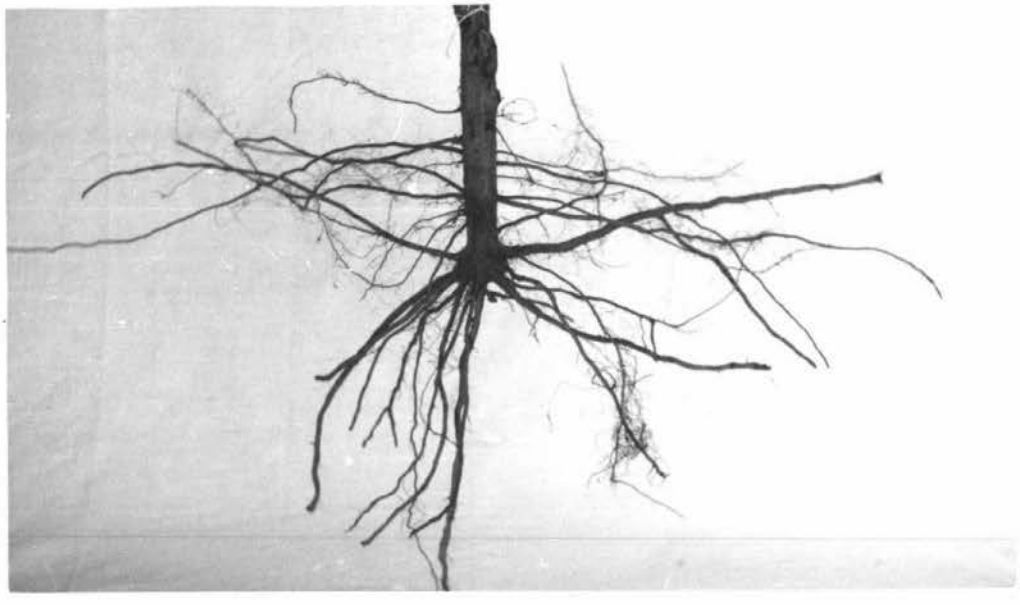
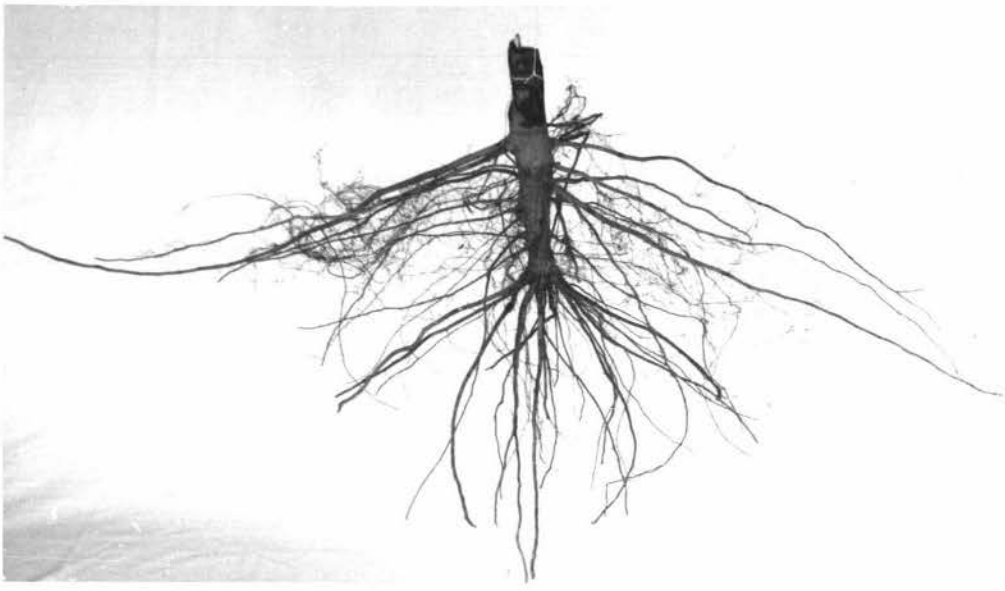


Fig. 4 cont.

Top : *P. yunnanensis*

Centre : *S. matsudana*

Bottom : *S. Booth*



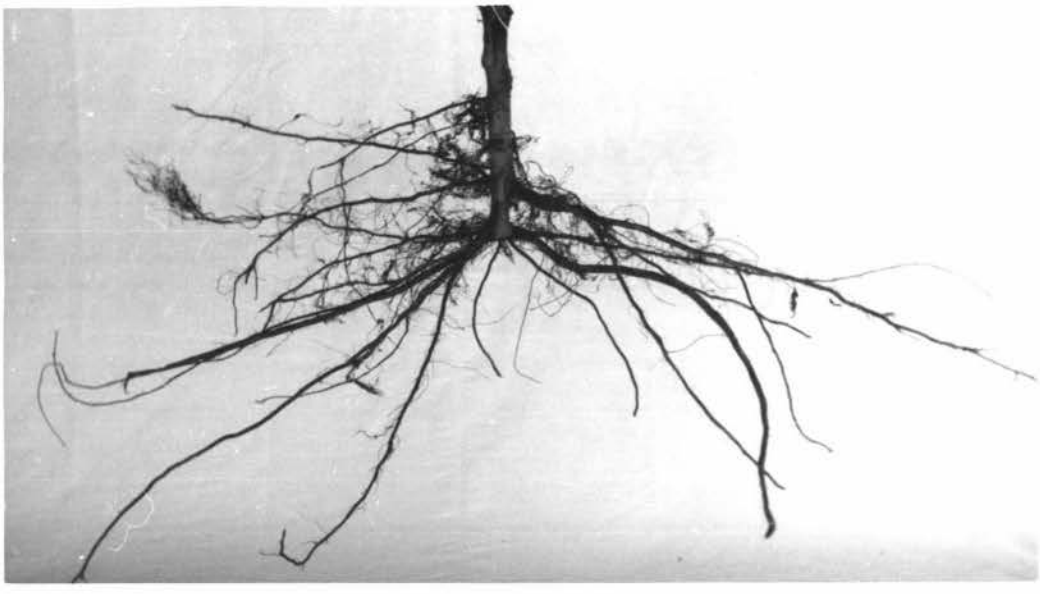
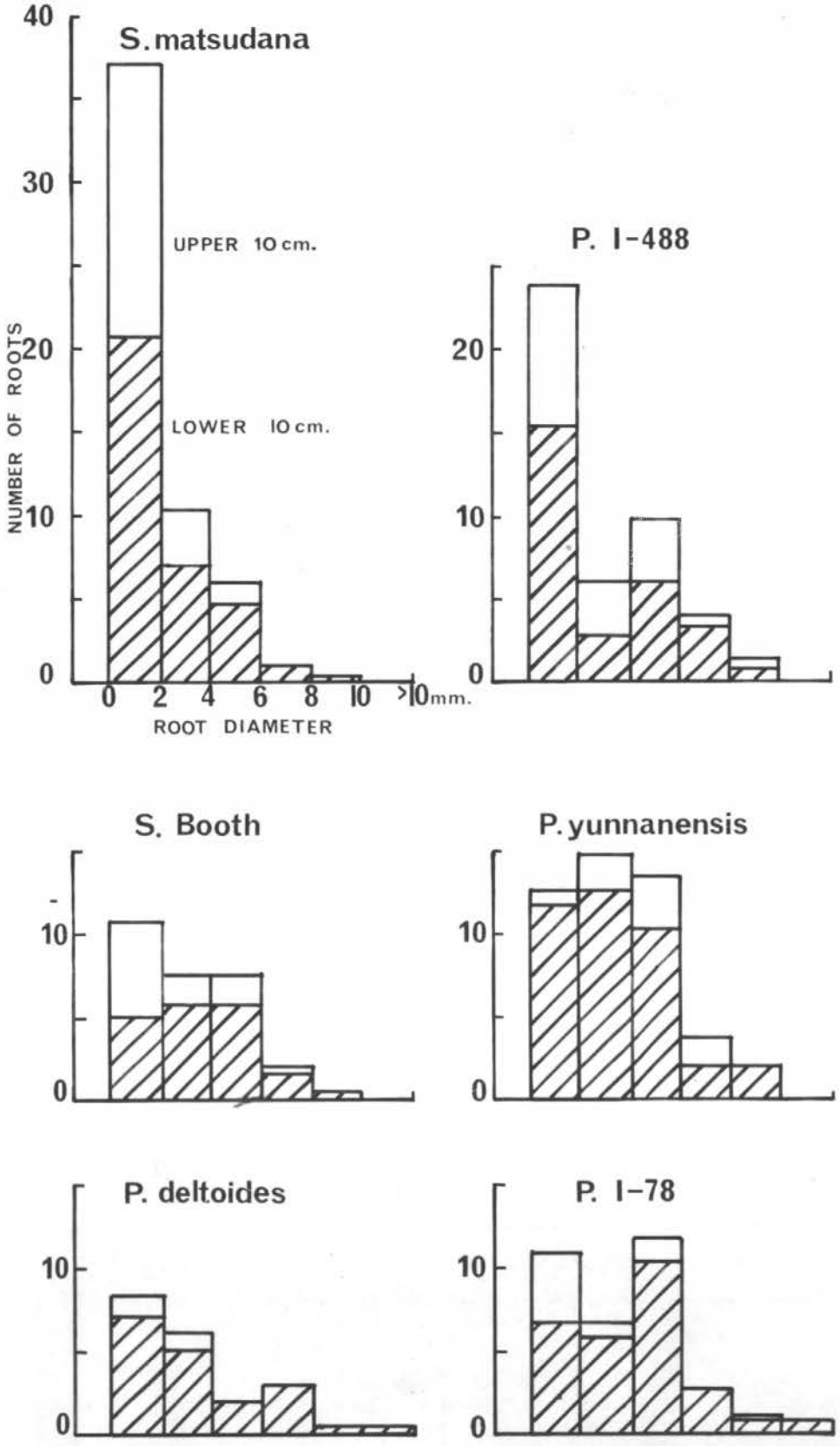


Fig. 5 Number and size of roots originating from the upper and lower regions of the cuttings



and horizontal roots well developed, although the horizontal roots were larger than the deeper penetrating roots. This indicates that the depth of rooting, at least in young trees, is genetically controlled in these species.

In general, the root systems of the poplars had a greater horizontal spread, and the willows a greater depth. The actual dimensions of the root systems were not determined and a quantitative comparison of the spread and depth of the root systems, to be of any real significance, would need to be undertaken on older trees grown at a wider spacing than those used in this study. Also, the one year old trees investigated showed considerable differences between clones in the size of the trees, and in the root systems. This was partly due to differences in the time of shoot initiation from the cuttings, and the effects would possibly disappear after several seasons growth. Also, initial differences in growth rate might not be maintained. The purpose of this part of the study was to determine whether there were any differences between clones in the form of their root systems, and if so, the effect of this on their soil binding capacity.

(iii) Amount of fibrous roots

There were large differences between clones in the amount of fibrous roots present in the root systems. The air-dry weight of fibrous roots (as a percentage of total air-dry weight of the root systems), of the three trees selected per clone, is given below.

	%	
S. matsudana	10.6	A
S. Booth	7.4	B
P. yunnanensis	7.1	B
P. I488	0.90	C
P. I78	0.65	C
P. deltoides	0.33	C

Values bearing the same letter were not significantly different at the 1% level. The analysis of variance is given in Appendix 13.

It can be seen that the two willow clones and P. yunnanensis had a considerably higher percentage of fibrous roots than did the other poplar clones.

It is of interest that the clones with the more deeply penetrating roots also had the highest percentage of fibrous roots. These features may be adaptations to drier sites, the deeper penetrating roots able to reach lower water tables, and the large number of fibrous roots providing a greater absorbing surface. However, the members of the genus Salix are characteristically found in regions of high soil moisture, and it appears then, that the willows may require a high water uptake, and these features are adaptations for this purpose. If this is so, it would be expected that greater transpiration rates would also occur, and these clones would be better suited than the others for erosion control purposes.

The root/shoot ratios were calculated to give an indication of whether this proportion was likely to be constant in a range of clones. If the root/shoot ratios were known, and were constant between clones, then an observation of the size of the shoot could provide an indication of the size of the root system. This would be very useful where a large number of clones were being examined for their suitability for erosion control purposes.

The investigation was not specifically designed for this purpose, and ideally would need to be replicated over a number of sites, using trees of various ages. However, as the data required for this calculation was available, ratios are given as an indication of the variability present.

The air-dry weights of roots and shoots and root/shoot ratios, for each of the three selected trees per clone are given in Appendix 8 together with the analysis of variance. Means are given below.

P. I78	.170 a
S. Booth	.146 ab
P. I488	.121 ab
P. deltoides	.115 b
S. matsudana	.074 bc
P. yunnanensis	.063 c

Values bearing the same letter were not significantly different at the 5% level.

It can be seen that quite large differences existed. For example, P. I78 had almost three times the weight of roots as P. yunnanensis per unit weight of shoot.

Although these results are of interest in themselves, obviously the size of the tree must also be taken into account when determining the value of the clone for soil conservation purposes.

The root/shoot ratios may also be taken as a measure of the efficiency of the tree in terms of root production. Most trees that are planted for erosion control purposes are subject to stress conditions for a large part of their life, especially in the initial stages of establishment in terms of water stress and nutrition. Trees that can utilise the available resources more efficiently in terms of root growth would possibly establish more quickly and also be more useful as an aid in soil stabilization.

3.2. Intra-clonal variation in the anatomy and tensile strength of individual roots

The anatomy and tensile strength of 20 roots of P. I488 was investigated as described in Section 2.2.2.

3.2.1. Anatomy

Anatomical measurements were obtained from microtome sections made close to where the root had broken during tensile testing, and from macerations of part of the test sample.

There were considerable differences in anatomy between individual roots, and quantitative data for each test sample are given in Appendix 9, together with the tensile strengths of the samples. The variation in percent fibre wall area, (15.1 - 25.6%), percent parenchyma and rays (5.2 - 10.2%) percent vessel area (36.8 - 49.5%), and vessel diameter (117-182 μ) is reflected in the variation in specific gravity (.210-.260). Mean fibre length varied from 727-913 μ, and microfibril angle from 34.5 - 39.3^{o}.

3.2.2. Tensile strength

A large amount of variation was seen in the tensile strength of the stele (2.38 - 4.96 kg/mm^2), while fibre wall strength and specific tensile strength showed approximately the same range (13.2 - 21.5 and 11.0 - 19.1 kg/mm^2 respectively).

3.2.3. Relation between tensile strength and anatomy

Correlation coefficients between the three tensile strength parameters and anatomical characteristics are given in Appendix 16. The three measures

of tensile strength were correlated with specific gravity at a highly significant level, tensile strength increasing with an increase in specific gravity. The high correlation of the tensile strength of the stele with specific gravity was anticipated, but the significant correlation of fibre wall strength and specific strength with specific gravity was unexpected, as these measures of tensile strength were designed to remove the effect of variation in the amount of cell wall material present. The tensile strength of the stele and specific strength were also highly correlated with percent fibre wall area, percent vessel area, and vessel diameter. Fibre wall strength and specific strength were significantly correlated with microfibril angle, strength increasing as the angle decreased. As the strength of the stele was highly correlated with fibre wall strength and specific strength, it appears that microfibril angle had an effect on the tensile strength of the stele, although this effect was largely over shadowed by the effect of specific gravity.

There was no indication of any relation between fibre dimensions and the measures of tensile strength. Even when the effects of variation in the amount of cell wall material were removed, no trends were evident.

All three tensile strength parameters were negatively correlated with the diameter of the stele, although none reached significant levels.

The regressions of the tensile strength of the stele on specific gravity and percent fibre wall area, specific gravity on percent fibre wall area, and fibre wall strength and specific strength on microfibril angle are shown graphically in fig. 6.

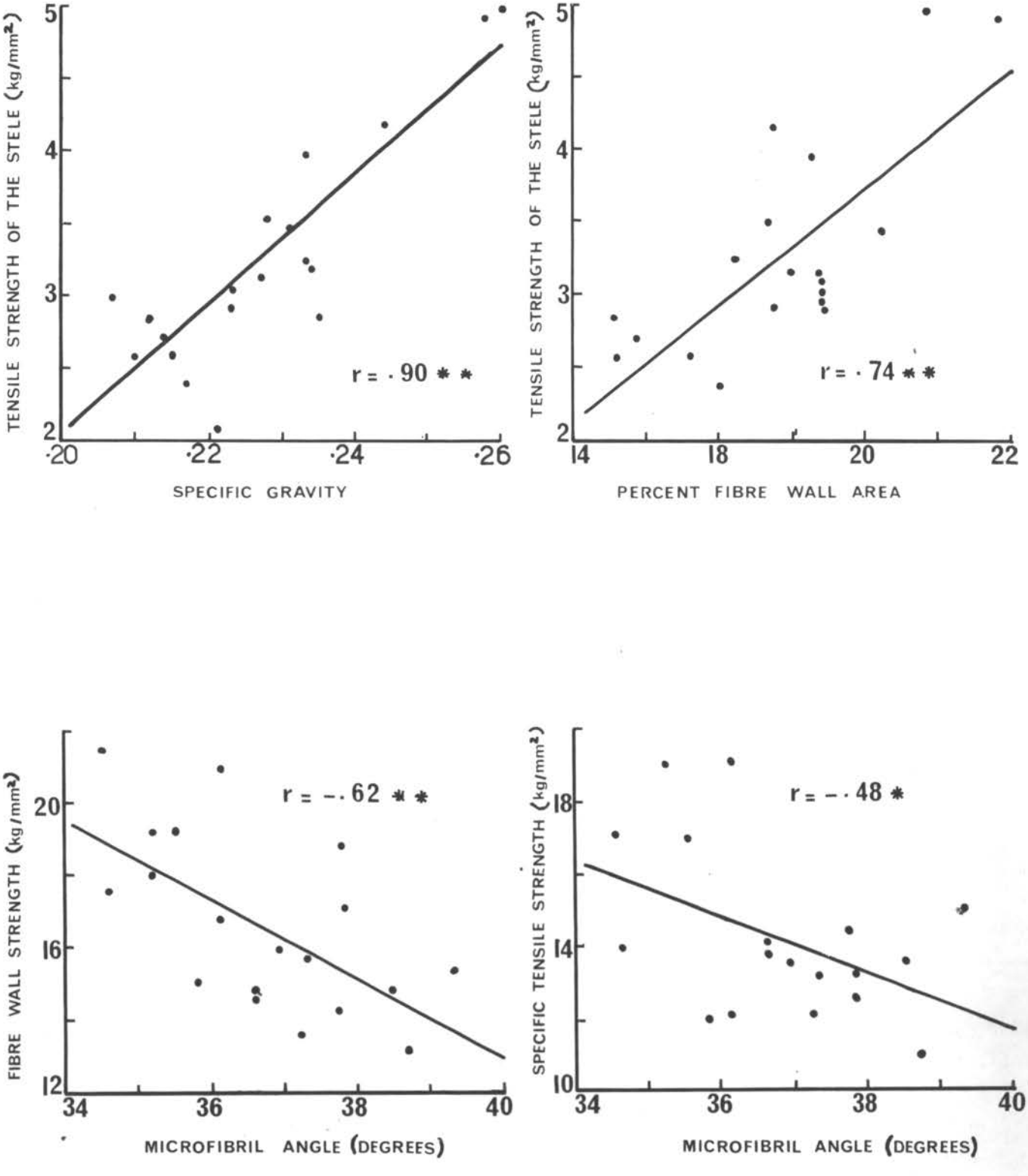
Multiple regressions of tensile strength on anatomical characteristics

The multiple regression analyses were carried out to determine the effect of a number of anatomical variables acting simultaneously to determine tensile strength and to determine the amount of variation in tensile strength that could be accounted for by these factors in combination.

i) Tensile strength of the stele

The simple correlation coefficients showed that the anatomical characteristics significantly correlated with the tensile strength of the stele were specific gravity, percent fibre wall area, percent vessel area,

Fig. 6 Relation between intra-clonal variation in anatomy, and tensile strength (P. I-488)



and vessel diameter. The correlation between diameter of the stele and tensile strength was not significant in the case of I 488 but other clones showed significant correlations (see Section 3.3.3), and the effect may have been masked by the other variables. As specific gravity and percent fibre wall area are essentially measures of the same parameter, only specific gravity was used in the multiple regression analysis.

The proposed model was :

$$Y = a + b_1 X_1 + b_2 X_2 + b_3 X_3 + b_4 X_4 + b_5 X_5 + E$$

where :

Y = tensile strength of the stele
X_1 = specific gravity
X_2 = diameter of the stele
X_3 = % vessel area
X_4 = vessel diameter
X_5 = % rays and parenchyma

b_1 to b_5 are the corresponding regression coefficients, a is a constant, and E is the error term. The regression coefficients are given in Table 1. The standardized partial regression coefficients (B) provide an indication of the importance of any particular anatomical feature in predicting the tensile strength of the stele.

Table 1 - Regression coefficients for the multiple regression of tensile strength of the stele on selected anatomical characteristics (see text).

	1	2	3	4	5
b	2.4249	-.2796	-1.0255	-.2216	.4963
B	.4881	-.1826	-.4485	-.0592	.0890

The analysis of variance of the multiple regression (Appendix 24) indicates that the diameter of the stele, vessel diameter and percent rays and parenchyma did not contribute significantly to the regression, while the contributions of specific gravity and percent vessel area were highly significant. The variance of the tensile strength of the stele attributable

to differences in specific gravity was 79.0%, and there was an increase to 85.5% when diameter and percent vessel area were included.

The purpose of the multiple regression analysis was not to construct a predicting equation for tensile strength, but to determine which anatomical features had the greatest influence on strength. Hence the value of the constant "a" in the above equation was not determined.

(ii) Fibre wall strength

The simple correlation coefficients showed that of the anatomical features likely to affect fibre wall strength, only microfibril angle was significantly correlated.

The following anatomical characteristics were used in the multiple regression.

Y = tensile strength of the fibre walls
X_1 = microfibril angle
X_2 = diameter of stele
X_3 = fibre length
X_4 = fibre width

The regression coefficients are shown in Table 2.

Table 2 - Regression coefficients for the multiple regression of fibre wall strength on selected anatomical characteristics (see text).

	1	2	3	4
b	-.8783	-.1661	.1527	.0329
B	-.4917	-.3254	.0842	.0600

The standardised regression coefficients indicate that microfibril angle and the diameter of the stele had the most effect on fibre wall strength. The analysis of variance, (Appendix 25) showed that only microfibril angle had a significant effect on fibre wall strength, although the contribution of the diameter of the stele reached a nearly significant level. The variance of fibre wall strength attributable to microfibril angle was 31.3%, and the addition of the diamter of the stele to the regression increased this to 36.7%.

(iii) Specific tensile strength

The same anatomical variables as in (ii) were used for the regression on specific strength, as these two strength parameters are essentially measuring the same thing.

Regression coefficients are given in Table 3.

Table 3 - Regression coefficients for the multiple regression of specific tensile strength on selected anatomical characteristics (see text).

	1	2	3	4
b	-.9844	-.2957	.4637	.1307
B	-.3504	-.4053	.1789	.1666

The standardised regression coefficients indicate that microfibril angle and diameter of the stele have the largest effects on specific strength. The analysis of variance (Appendix 26) showed that only microfibril angle contributed significantly to the regression. The individual contributions of diameter of the stele, fibre length, and fibre width did not even approach significance. The variance of specific strength attributable to microfibril angle was only 19.3%.

3.3. Inter-clonal variation in anatomy, chemical composition, tensile strength, and stress/strain relationships of individual roots

The objective of this part of the study was to investigate the anatomy and chemical composition of roots of the six clones, and to determine whether any variation present was correlated with any differences between clones in the tensile strength of the roots. The stress/strain behaviour of a number of roots was also investigated.

The methods and procedure followed in the investigation are described in Section 2.2.3.

The number of samples required to give significant differences in tensile strength was determined from the results of the study of intra-clonal variation in the tensile strength of the stele in P. I488. It was

assumed for this purpose that all the clones would show similar standard deviations to that of P. I488 in the tensile strength of the stele. It was calculated that for a 10% difference in the means between clones to be significant at the 5% level, 10 samples of each clone were required. If 20 samples were used, a 6.8% difference in the means would be significant at the 5% level. It was thus decided that 20 samples would be adequate to determine any differences in the tensile strength of the stele that would be of any practical significance, and as the coefficients of variation of fibre wall strength and specific tensile strength were less than that for the strength of the stele, would also show adequately the differences between these parameters.

3.3.1. Anatomy

As the cortex appeared to have little effect on the loads required to break the roots, only the anatomy of the stele was investigated. However, there was considerable variation in the proportion of stele to cortex between clones, and this explained much of the variation in the overall tensile strength of the roots noticeable in the field.

The means of the percentage of the cross-sectional area of each root that was stele, for all the roots of each clone tested for tensile strength, are given below.

S. matsudana	50.3	A
S. Booth	47.1	AB
P. yunnanensis	46.1	B
P. I488	30.7	C
P. I78	27.5	CD
P. deltoides	25.1	D

Values bearing the same letter were not significantly different at the 1% level.

Transverse sections of the steles of all the roots tested were prepared (Section 2.3.5) and typical sections of each clone are shown in fig. 7.

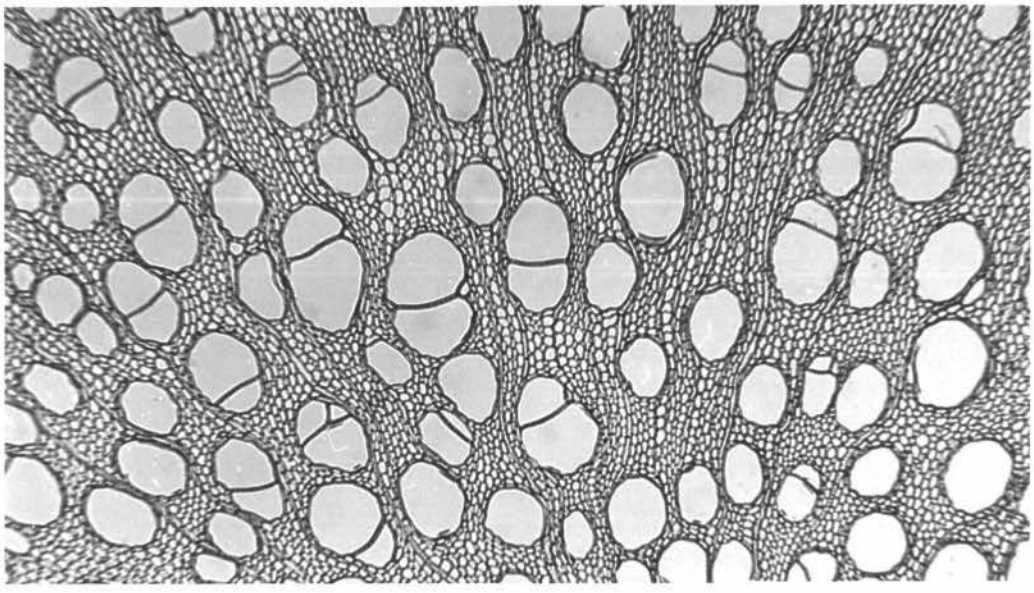
Roots of all clones showed a fairly even distribution of vessels throughout the stele, although a number of roots showed fewer vessels nearer the cambium. Early wood and late wood were not clearly differentiated,

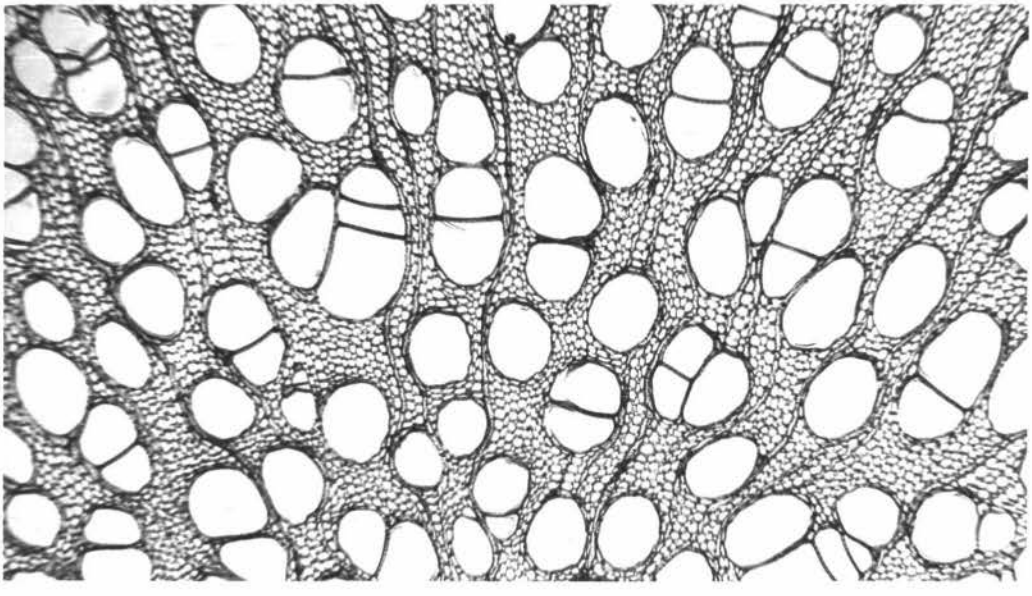
Fig. 7 Typical transverse sections of the steles of the roots (X60)

Top : P. I-78

Centre : P. I-488

Bottom : P. deltoides





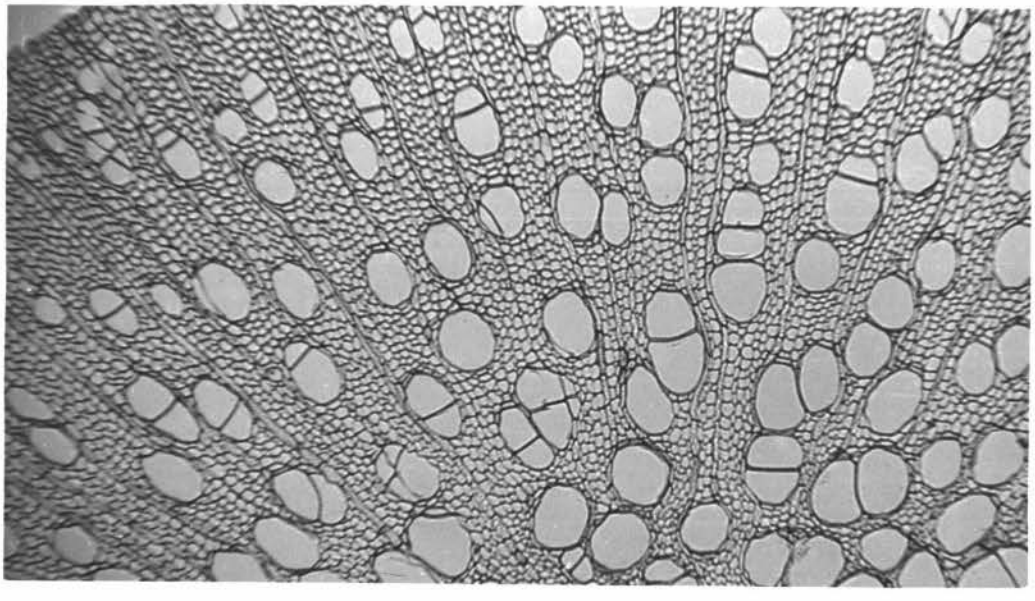
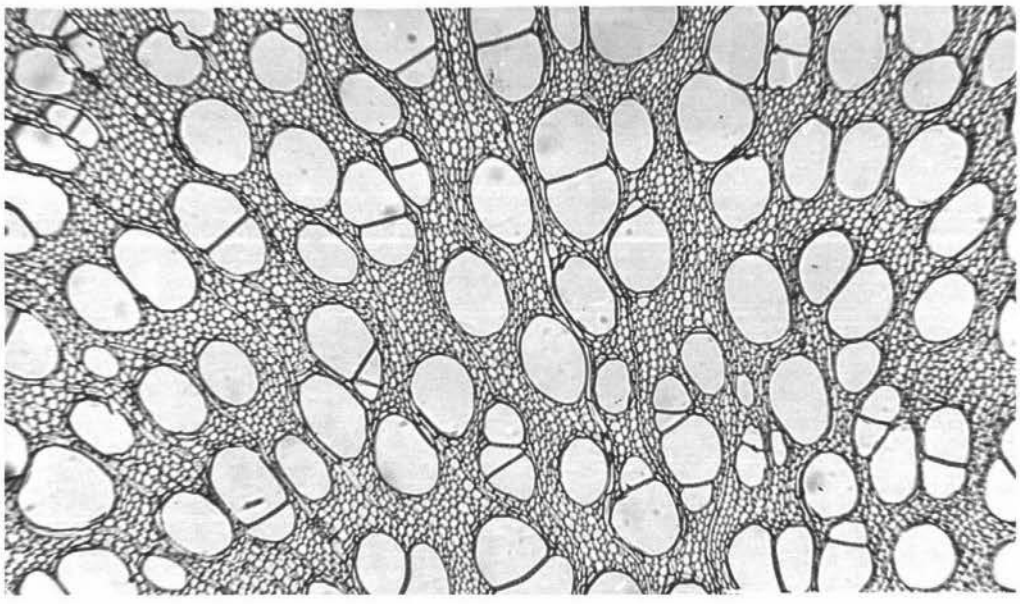


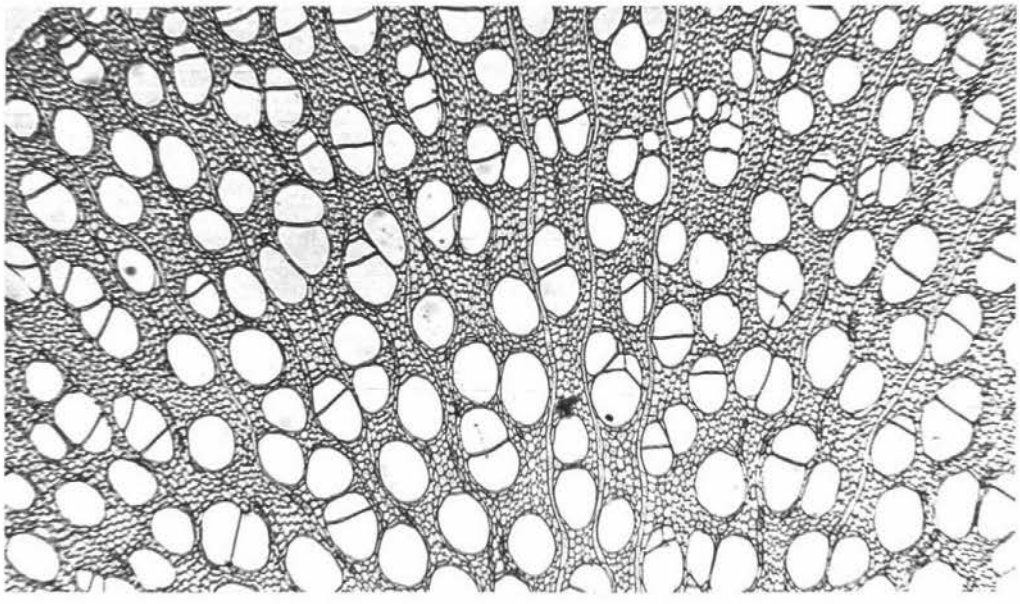
Fig. 7 cont.

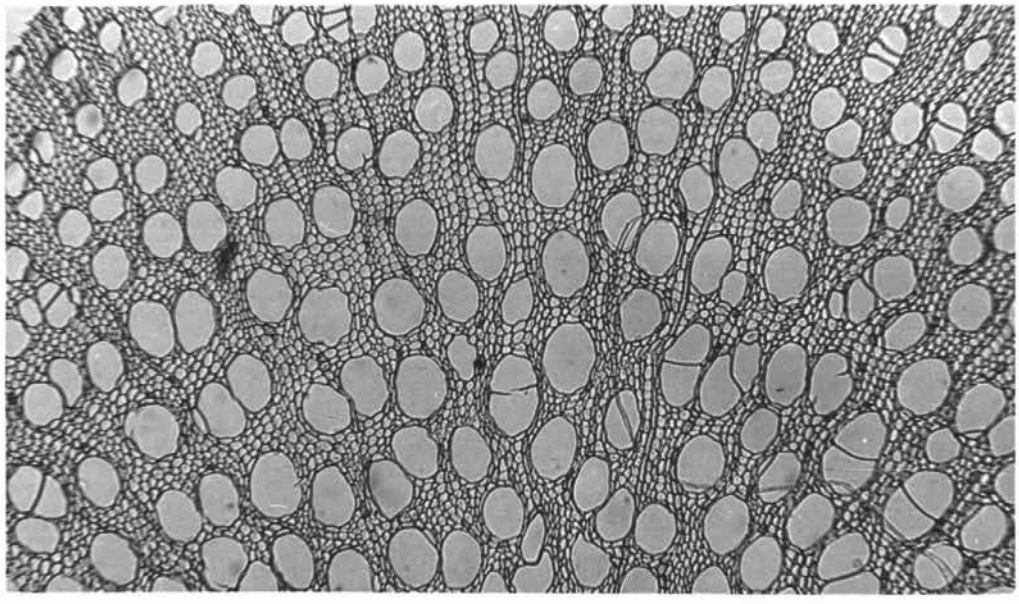
Top : *P. yunnanensis*

Centre : *S. matsudana*

Bottom : *S. Booth*







and small vessels and thick walled fibres occurred only in the outer few cell layers of most samples, accounting for only a small percentage of the total cross-sectional area. Small vessels and fibres occurred near the centre of the stele, but there was no pith as such.

Most fibres were of the libriform type, with simple slit pits, and only occasional fibre tracheids were seen, with bordered pits. Fibres showed the three layers of the secondary wall typical of stemwood fibres. (Figure 8). Gelatinous fibres were common in the steles of S. matsudana and S. Booth roots (Figures 9 & 10), but none were seen in any of the poplar clones. In the two willow clones, they were usually found in the central half of the stele. They did not appear to be more common in roots with eccentric development.

Rays were fine and uniseriate, and most parenchyma was of the paratracheal type. In the poplars, only the rays and parenchyma were filled with starch grains, but in the willows, many fibres were also used as storage sites for starch. (Fig. 10).

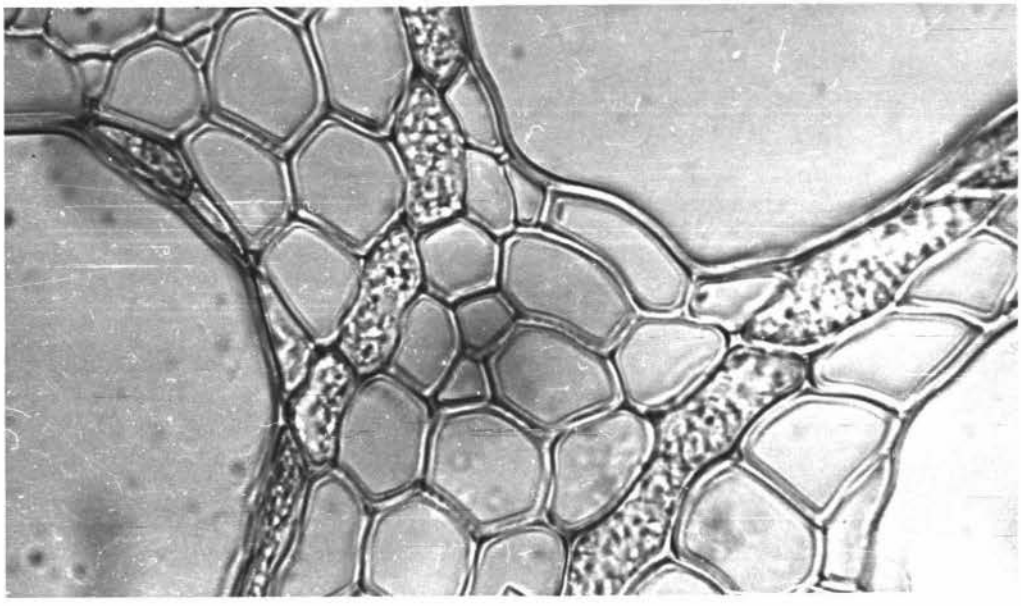
All clones showed multiple vessel groups, although these tended to be more numerous in the poplars. There were differences between clones in the sizes and number of vessels. The willows had vessels with the smallest diameter (mean of tangential and radial measurements), while P. I488 and P. deltoides had the largest. P. I78 had considerably less of the total cross-sectional area of the stele occupied by vessels. P. I488 and P. deltoides had the largest area occupied by rays and parenchyma.

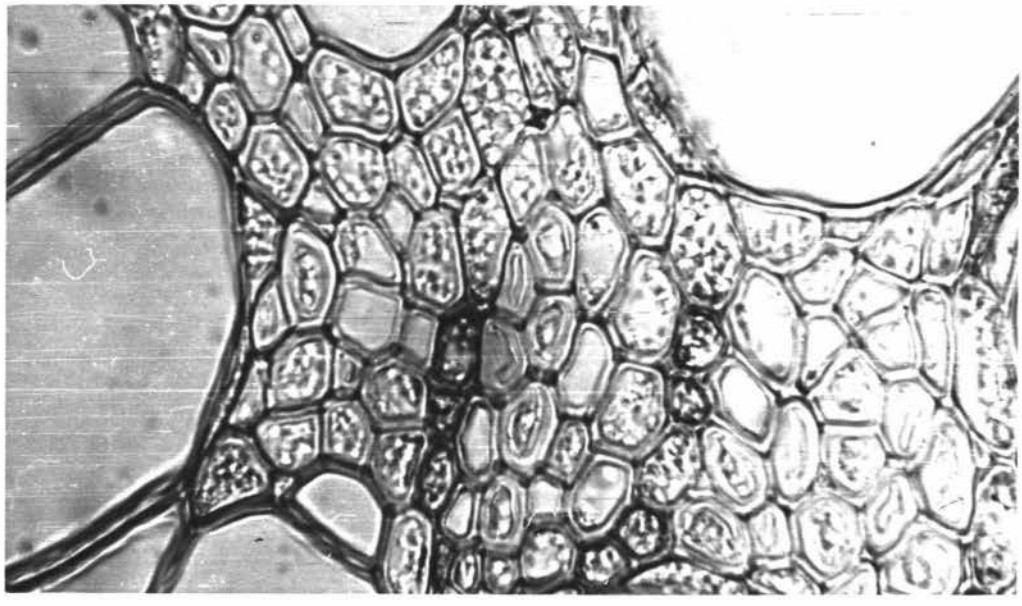
Quantitative anatomical data was obtained from single roots of each clone, with steles of the same diameter (3mm), and values for the tensile strength of the stele closest to the adjusted mean for the clone from the covariance analysis - see Section 3.3.3. Results are given in Table 4. It was not possible in the time available to determine quantitatively all the anatomical characteristics of all the samples used in the investigation.

Fig. 8 Transverse section of root of P. I-488, showing the three-layered structure of the secondary wall (X600)

Fig. 9 Transverse section of a root of S. matsudana, showing gelatinous fibres (X600)

Fig. 10 Transverse section of a root of S. Booth, showing gelatinous fibres, and presence of starch grains in both parenchyma and fibres (X240)





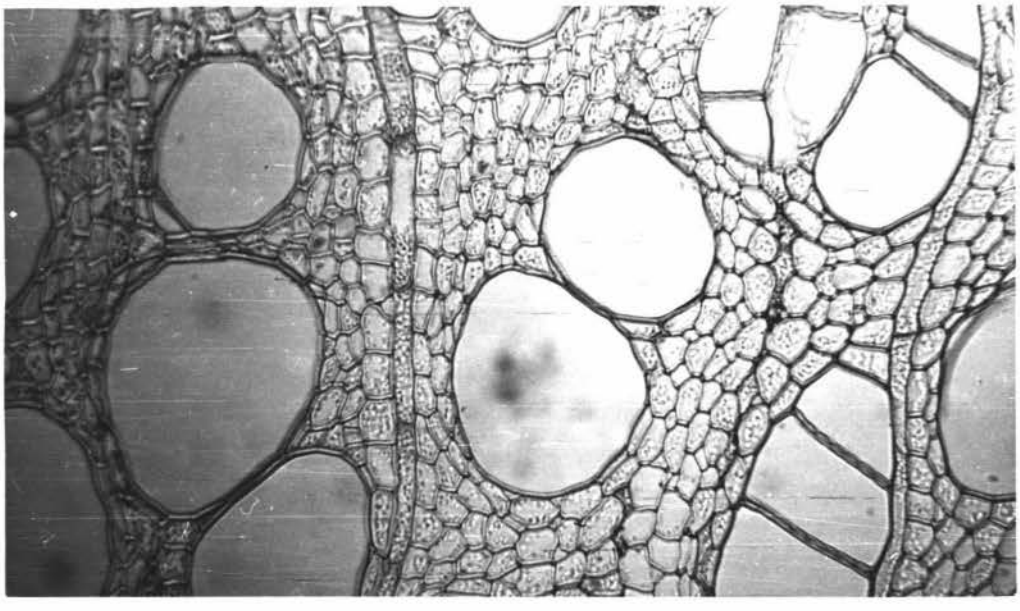


Table 4 - Anatomical data of roots of each clone with steles of the same diameter (3mm) and values for the tensile strength of the stele closest to the adjusted mean for the clone.

	tensile strength of stele (kg/mm^2)	fibre wall strength (kg/mm^2)	specific strength (kg/mm^2)	specific gravity	% fibre wall area	% vessel area	vessel diameter (μ)	% parenchyma + rays	microfibril angle (^{o})	fibre length (μ)	fibre width (μ)
P. I488	3.10	14.9	14.1	.221	20.7	45.5	158	10.2	36.3	891	22.7
P. yunnanensis	4.15	19.0	17.6	.236	21.9	44.4	142	6.8	37.0	725	19.3
P. I78	4.89	18.9	18.1	.270	25.9	30.0	125	7.8	36.0	806	27.2
S. matsudana	3.82	15.4	14.4	.264	24.8	44.8	122	4.5	39.7	760	20.4
S. Booth	3.67	16.7	15.2	.241	22.0	40.3	112	6.0	38.1	732	23.9
P. deltoides	3.20	16.7	13.1	.245	19.1	37.2	164	10.5	36.1	818	25.3

3.3.2. Chemical composition

The chemical composition typical of the roots of each clone was determined from bulked samples of all the roots tested for tensile strength (see Section 2.3.12). Table 5 shows the composition of the roots of each clone on a total dry weight basis, and Table 6 shows the composition corrected for starch content. This was necessary due to the large amount of starch present in the roots during the dormant period, when the samples were collected (see Appendix 15). The starch was not a component of the cell wall, and thus had no structural function.

The difference in cellulose content as determined by hydrolysis to glucose and by the method of Cross and Bevan, was due to the methods of determination. Cellulose determined by hydrolysis is essentially pure cellulose, while that determined by the method of Cross and Bevan contains other resistant non-cellulosic polysaccharides that may have a structural function (see Section 1.8.1). There was some discrepancy in the ranking of clones with respect to cellulose content as determined by the two methods. S. Booth and P. I78 were highest in both cellulose by hydrolysis and by the Cross and Bevan method, and P. deltoides had the lowest. However, S. matsudana and P. yunnanensis were high in "Cross and Bevan" cellulose, but low in cellulose by hydrolysis, while P. I488 was low in "Cross and Bevan" cellulose, but high in cellulose by hydrolysis. This discrepancy was possibly due to some difference between clones in the amount or type of non-cellulosic polysaccharides included in the determination by the method of Cross and Bevan.

There was considerable variation in the hemicellulose and lignin contents between clones, although the hemicellulose determination could not be relied upon to be accurate (see Section 1.8.1).

Table 5 - Chemical composition expressed as a percentage of the total dry weight

	extractives	cellulose (by hydrolysis)	cellulose (Cross & Bevan)	Lignin	Hemicellulose	Starch	Lignin / cellulose (hyd)	Lignin / cellulose (C&B)
S. matsudana	8.2	34.1	48.7	15.5	15.6	16.5	.455	.404
S. Booth	4.3	42.0	54.6	13.7	13.0	10.3	.326	.251
P. I488	7.7	39.2	44.2	17.9	12.1	9.8	.457	.405
P. I78	5.6	41.8	56.7	17.7	16.5	5.9	.423	.312
P. deltoides	9.2	35.5	46.6	16.3	16.0	8.0	.459	.349
P. yunnanensis	7.4	38.7	54.2	17.7	17.4	6.0	.457	.326

Table 6 - Chemical composition expressed as a percentage of the starch free dry weight

	extractives	cellulose (by hydrolysis)	cellulose (Cross & Bevan)	Lignin	Hemicellulose	Lignin / cellulose (hyd)	Lignin / cellulose (C&B)
S. matsudana	9.8	40.8	58.3	18.6	18.7	.456	.319
S. Booth	4.8	46.8	60.9	15.8	14.5	.338	.259
P. I488	8.5	43.5	49.0	19.8	13.4	.455	.404
P. I78	6.0	44.4	60.2	18.8	17.5	.423	.312
P. deltoides	10.0	38.6	50.6	17.7	17.4	.458	.349
P. yunnanensis	7.9	38.7	57.6	18.8	18.5	.486	.326

3.3.3. Tensile strength

The tensile testing of the roots was carried out as described in Section 2.3.2, and the tensile strength of the stele, fibre wall strength, and specific strength of individual roots of the six clones are given in Appendix 10.

It was found that in all cases the strength of the stele, fibre wall strength, and specific strength were negatively correlated with the diameter of the test samples, although not always at a significant level. The correlation coefficients and regression equations are given in Appendix 18.

As there was some variation between clones in the spread of the diameters of the test samples, this correlation between size and strength meant that the means of all the samples tested could not be used for a comparison between clones, as they were likely to be biased. To overcome this, the adjusted means from analyses of covariance (Appendix 21), with the diameter of the samples being taken into account, were used in comparing clones. The adjusted means of tensile strength of the stele, fibre wall strength, and specific strength are shown in Fig. 11. The stele of roots of *P. I78* was significantly greater in overall tensile strength, but there were no significant differences between the remaining clones. There were no significant differences between clones in fibre wall strength, although *P. I78* still appeared to be strongest in this respect. *P. I78* was also significantly greater in specific tensile strength. *P. deltoides* was significantly weaker than *P. I78* and *P. yunnanensis*.

3.3.4. Relation between anatomy, composition and tensile strength

The relationship of mechanical properties of plants to anatomical features is obviously complex, but in this study some correlations were evident. Table 7 shows the correlation coefficients between anatomical characteristics and tensile strength parameters of the samples selected as being representative of the clones used in the study. Because the number of samples used in the analysis was so small, a large correlation coefficient ($r = .73$) was required to indicate a significant relationship (5% level).

Fig. II Inter-clonal variation in the tensile strength of roots (means adjusted for root diameter)

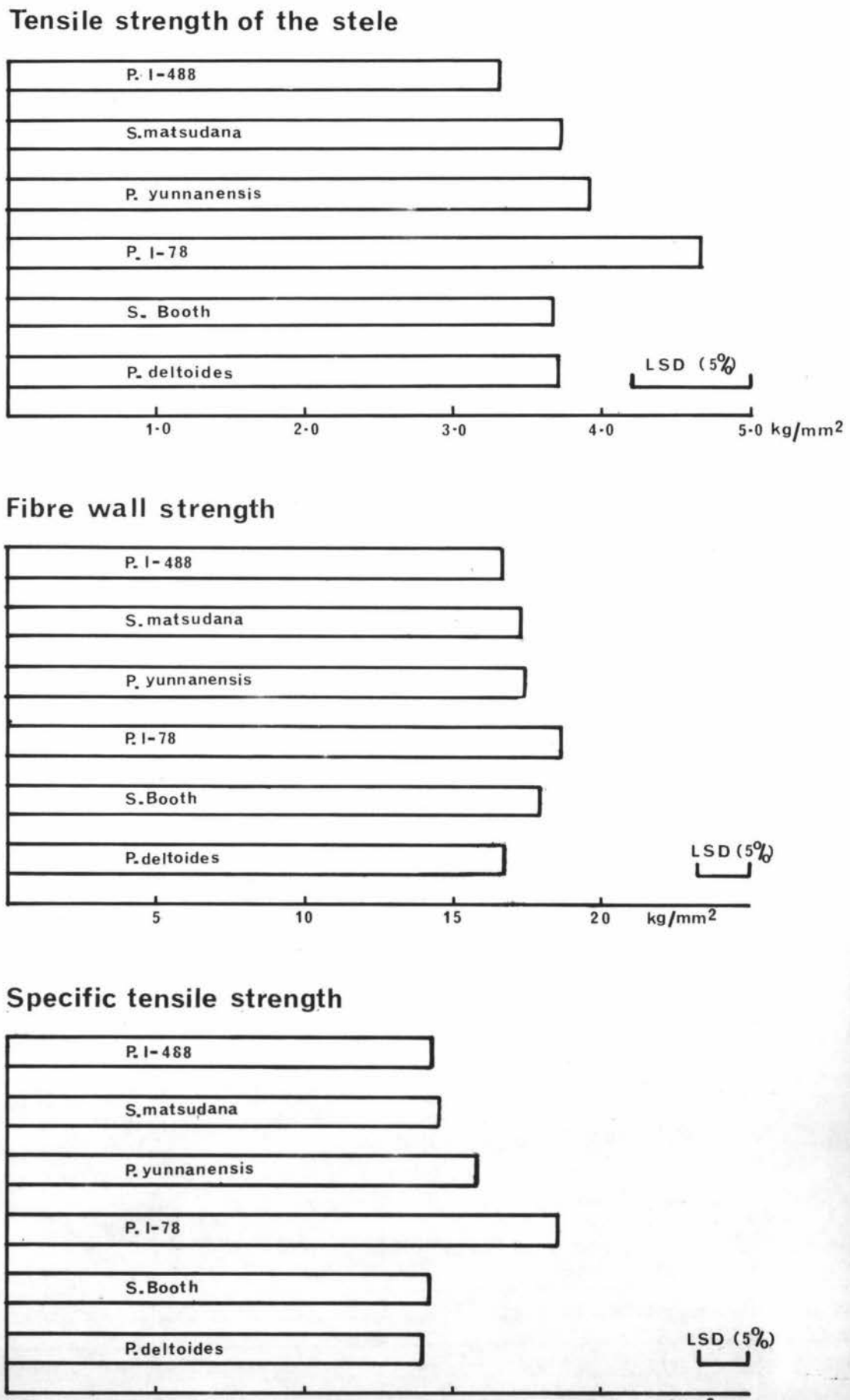


Table 7 - Correlation coefficients between interclonal variation in anatomical characteristics and tensile strength

	tensile strength of stele	fibre wall strength	specific tensile strength	specific gravity	% fibre wall area	% vessel area	vessel diameter	% parenchyma and rays	Microfibril angle	mean fibre length	mean fibre width
tensile strength of stele	1	.78*	.91**	.70	.83*	-.58	-.57	-.45	-.03	-.41	.20
fibre wall strength		1	.85*	.33	.30	-.55	-.19	-.10	-.38	-.47	.17
specific strength			1	.33	.62	-.38	-.43	-.33	-.18	-.40	.02
specific gravity				1	.73*	-.61	-.54	-.47	.28	.13	.34
% fibre wall area					1	-.34	-.74*	-.65	.36	-.24	.08
% vessel area						1	.16	-.21	.49	-.07	-.89
vessel diameter							1	.86*	-.63	.65	.01
% parenchyma and rays								1	-.86*	.79*	.46
microfibril angle									1	-.56	-.57
fibre length										1	.40
fibre width											1

Variation between clones in the tensile strength of the stele was significantly correlated with fibre wall strength, specific strength, and percent fibre wall area, and almost significantly with specific gravity. Fibre wall strength was significantly correlated with specific strength, as both are measures of the strength of the cell walls. Specific gravity was significantly correlated with percent fibre wall area, as was expected. The other significant correlations between percent vessel area, percent parenchyma and rays, microfibril angle, and fibre dimensions were probably coincidental.

It can be seen that trends evident in the relation between anatomy and tensile strength in the investigation of intra-clonal variation in P. I488 also existed between clones, but the correlations failed to reach significant levels. This was probably due to the small number of samples, and in the case of fibre wall strength and specific tensile strength, lack of variation in tensile strength between clones.

The alternatives to using a representative sample of each clone to study the relation of strength to anatomy were, firstly, to measure all the anatomical characteristics of all the roots of each clone tested. This was not done in this study, due to the time involved to obtain accurate quantitative data for all the samples. Secondly, a larger range of clones could have been used.

The relation between inter-clonal variation in composition and tensile strength was obtained using the composition of the bulked samples of the roots (see Section 3.3.2) and the adjusted means from the covariance analysis (Appendix 21). The adjusted means were used as the bulked samples consisted of equal amounts of root material of the roots tested, irrespective of the diameter of the root. Correlation coefficients are shown in Table 8.

Table 8 - Correlation coefficients between inter-clonal variation in composition, and tensile strength.

	extract-ives	cellulose (by hydro-lysis)	cellulose (by C & B)	Lignin	Hemi-cellulose	Lignin/ cellulose (Hyd)	Lignin/ cellulose (C & B)
tensile strength of stele	-.39	.09	.61	.03	.53	-.05	-.41
fibre wall strength	-.78*	.57	.87*	.24	.17	-.50	-.69
specific strength	-.39	.20	.50	.23	.33	.02	-.20

The inter-clonal variation in the tensile strength of the stele was not significantly correlated with any particular chemical component, and this was probably due to the over-riding effect of specific gravity. Fibre wall strength was significantly correlated with "Cross and Bevan" cellulose content, and fairly highly correlated with cellulose as determined by hydrolysis. Specific strength was also positively correlated with cellulose as determined by both methods, but not at significant levels. None of the strength parameters were correlated with lignin content at anywhere near significant levels. The significant correlation of fibre wall strength with extractive content was not expected, as most extractives are not present in the cell wall.

It appears from these results that inter-clonal variation in the tensile strength of the stele depends mainly on differences in specific gravity, and variation in the strength of the cell walls, as indicated by fibre wall strength and specific strength, depends mostly on differences in cellulose content. However, these relationships cannot be conclusive, due to the small number of clones used in the investigation, and the effect of inter-actions between anatomical variables and composition.

3.3.5. Stress/strain behaviour

The main purpose in investigating the stress/strain behaviour of individual roots was to give an indication of differences between clones of the elasticity of the roots, and the amount of extension that was possible before failure occurred. A root with elastic properties and a high degree of elongation before failure occurs is possibly more suitable for soil stabilisation purposes than a root that will not give with the soil movement.

Load/extension curves were obtained as described in Section 2.3.2 for four roots of each clone covering a range of diameters and these were converted to stress/strain diagrams. Young's modulus, ultimate strain (strain at failure) and ultimate stress/ultimate strain were obtained from the diagrams and are given in Appendix 12. Mean values are given in Table 9, and typical stress/strain curves in fig. 12.

Fig. 12 Stress/strain behavior.

The solid lines are typical stress/strain curves and the broken lines the extreme curves.

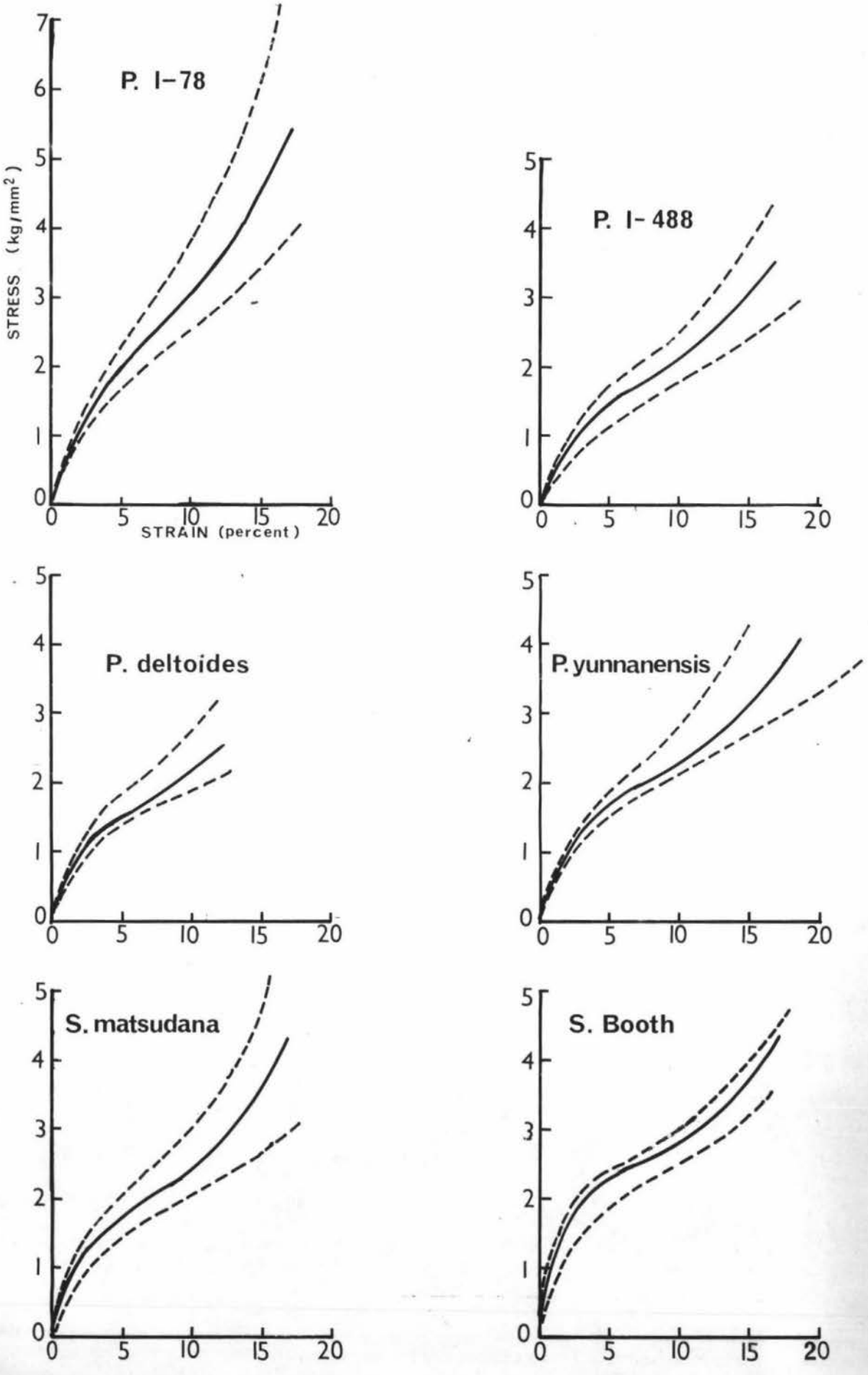


Table 9 - Stress/strain characteristics of roots of the six clones.

clone	Young's modulus (kg/mm^2)	ultimate strain (%)	ultimate stress / ultimate strain
P. I78	1.67 a	17.1 a	.326 a
S. Booth	1.61 a	17.3 a	.248 a
P. yunnanensis	1.23 b	18.7 a	.226 a
S. matsudana	1.10 bc	16.9 a	.254 a
P. deltoides	0.92 bc	12.4 b	.220 a
P. I488	0.89 c	16.8 a	.209 a

Values with the same letter (within each column) are not significantly different at the 5% level.

Young's modulus was significantly higher in roots of P. I78 and S. Booth than those of the other clones, indicating that they could be extended to a lesser degree than roots of the other clones before incurring permanent deformation. Roots of P. deltoides were significantly less in ultimate strain, extending considerably less than roots of the other clones before breaking. However, there were no significant differences between clones in the ratio of ultimate stress/ultimate strain.

There appeared to be some decrease in ultimate strain and modulus of elasticity with an increase in the diameter of the stele, but there were insufficient samples covering a range of diameters for statistical analysis. A decrease in these parameters with increasing diameter would be expected (see Section 1.5).

As well as differences between clones in Young's modulus and ultimate strain, there were further differences in the snape of stress/strain curves. For example, P. I78 and S. Booth both showed similar moduli of elasticity, but roots of S. Booth yielded more easily beyond the proportional limit than those of P. I78.

It was considered likely that the variation shown to be present in Young's modulus and ultimate strain was related to the anatomical and chemical characteristics of the clones.

The correlation coefficients between the means of Young's modulus and ultimate strain and the composition and specific gravity typical of the clones are given in Table 10.

Table 10 - Correlation coefficients between inter-clonal variation in Young's modulus and ultimate strain, and specific gravity and composition of individual roots.

	specific gravity	Cellulose (Cross & Bevan)	Cellulose (Hydrol.)	Lignin	Lignin cellulose (C&B)	Lignin cellulose (Hydrol.)
Young's modulus	.47	.87*	.64	-.47	-.80*	-.67
ultimate strain	-.20	.57	.34	.17	-.27	.44

Young's modulus was correlated with cellulose content (as determined by the Cross & Bevan method) and negatively correlated with the ratio of lignin to cellulose, both at a significant level. This indicates that roots of clones with higher cellulose contents and lower lignin/cellulose ratios were less elastic (i.e. could sustain less elongation without incurring permanent deformation). Clones with roots with high lignin contents and lignin/cellulose ratios were more elastic.

3.4. Soil binding capacity of the root systems

The load required to remove the root system of each tree vertically from the soil was used as a measure of soil binding capacity (see Section 2.3.1). This method has several disadvantages, and can only be regarded as an estimate. The feature most open to criticism is that the load was not distributed evenly over the whole root system in those trees with a number of large horizontal roots close to the ground surface. These horizontal roots occasionally broke sometime after the maximum load had been reached, and thus were not contributing in full to the estimate of soil binding capacity.

The loads required to remove each of the 10 trees per clone are given in Appendix 6 together with the analysis of variance. Means are given below:

S. matsudana	366 kg	a
P. yunnanensis	351	ab
P. I78	337	b
S. Booth	249	c
P. I488	209	d
P. deltoides	108	e

Values bearing the same letter are not significantly different at the 5% level.

It is apparent that there were considerable differences in the loads required to remove the trees from the soil, and the few roots that did not break at the maximum load could not have created such large differences. It was thus assumed that this measurement was a satisfactory indication of soil binding capacity. However, it was obvious that differences in tree size were causing much of the variation in soil binding capacity. To enable comparisons of soil binding capacity to be made with regard to the morphology of the root systems, a "root system strength index" was calculated. This was defined as the load required to remove the root system divided by the total air-dry weight of roots, and so removed the effect of the size of the root system on soil binding capacity.

The root system strength indices were calculated for the three selected trees per clone, and are given in Appendix 7 together with the analysis of variance. Means for each clone are given below:

S. matsudana	8.42	a
S. Booth	6.53	ab
P. yunnanensis	5.33	bc
P. I78	4.93	bcd
P. I488	3.55	cd
P. deltoides	2.61	d

Values bearing the same letter were not significantly different at the 5% level.

3.5. Effect of variation in root system morphology, and anatomy and tensile strength of individual roots, on soil binding capacity

To enable any such relationship to be determined, the above morphological, anatomical and tensile strength data are summarized in Table 11.

Table 11 - Ranking of morphological, anatomical, tensile strength characteristics, and soil binding capacity of each clone.

	Depth of root system	Angle of major roots with horizontal	Amount of fibrous roots	Ratio of stele to cortex	Tensile strength of the stele	Load required to remove the root system	Root system strength index
P. I78	4	3	5	5	1	3	4
P. I488	5=	5=	4	4	6	5	5
P. yunnanensis	3	4	2=	2=	2	2	2
P. deltoides	5=	5=	6	6	4	6	6
S. matsudana	1	1	1	1	3	1	1
S. Booth	2	2	2=	2=	5	4	2

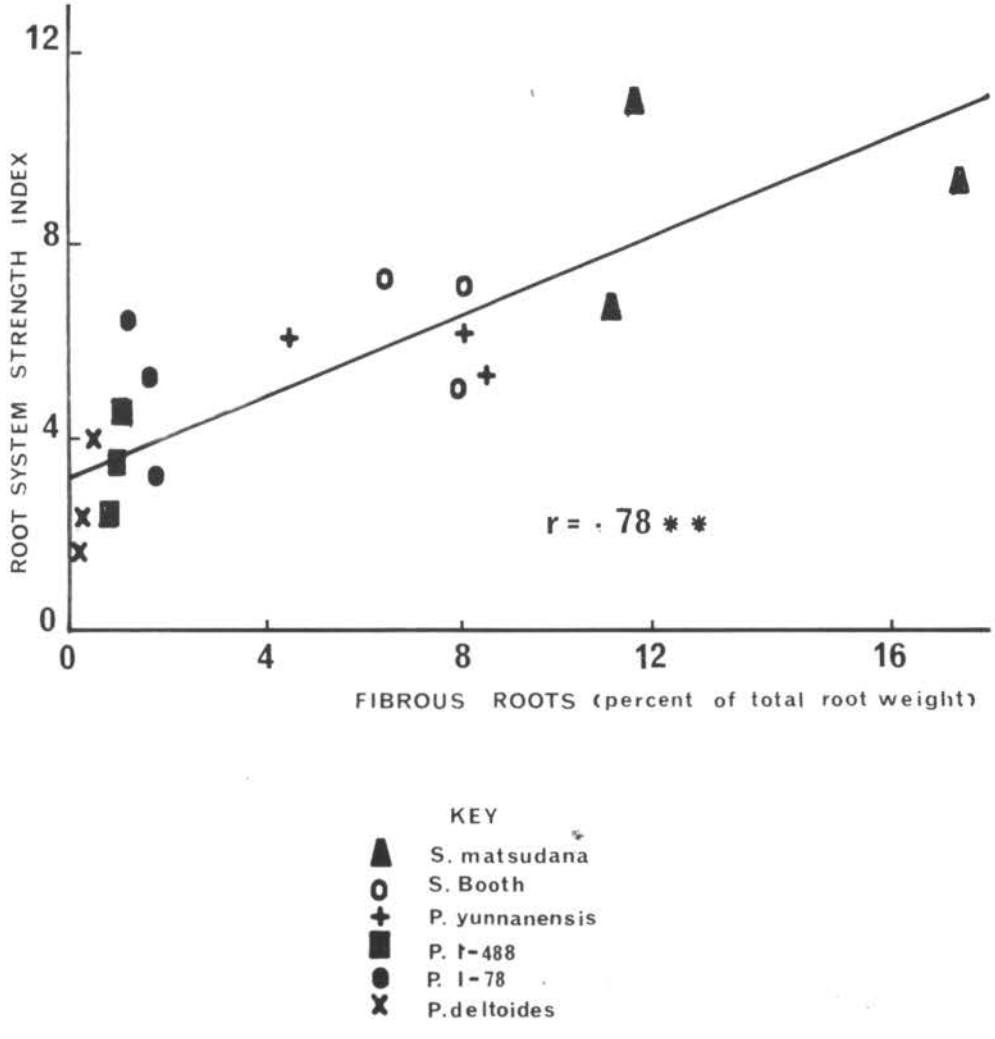
Ranking : Greatest value = 1
Smallest value = 5

It appears from the ranking in Table 10 that the features most closely associated with the root system strength indices are amount of fibrous roots, depth of the root system, the angle of the major roots, and the ratio of stele to cortex.

The three clones with the highest root system strength indices (S. matsudana, S. Booth, and P. yunnanensis) were also found to have the highest percentage of fibrous roots (see Section 3.1.1) and it is possible there is a relationship between these factors. The regression of root system strength index on percent fibrous roots is shown in fig. 13.

It can be seen from fig. 4 that these three clones also had more deeply penetrating roots, and the effect of the amount of fibrous roots on the root system strength index may in fact be confounded with the number of deeper penetrating roots. However, the root system of S. Booth consisted

Fig.13 Relation between Root System Strength Index and proportion of fibrous roots



mostly of large deeply penetrating roots, while that of P. yunnanensis had fewer and smaller deeper penetrating roots, but the proportion of fibrous roots present and the root system strength index of the two clones were approximately equal. If the effect of the large deep roots of S. Booth on the root system strength index had been substantial, it would be expected that the strength index would have been considerably higher than that of P. yunnanensis.

The contribution of the fibrous roots in the root systems to the soil binding capacity was also determined by comparing the predicted loads required to remove the root systems (based on the strength of roots greater than 1mm. in diameter) with the actual loads that were measured. The predicted loads were calculated as described in Section 2.2.1, and as the fibrous roots were not taken into account in the calculation, the difference between the predicted and actual loads was an estimate of the contribution to the soil binding capacity of the fibrous roots together with the friction between all the roots up to the breaking point, and the soil particles.

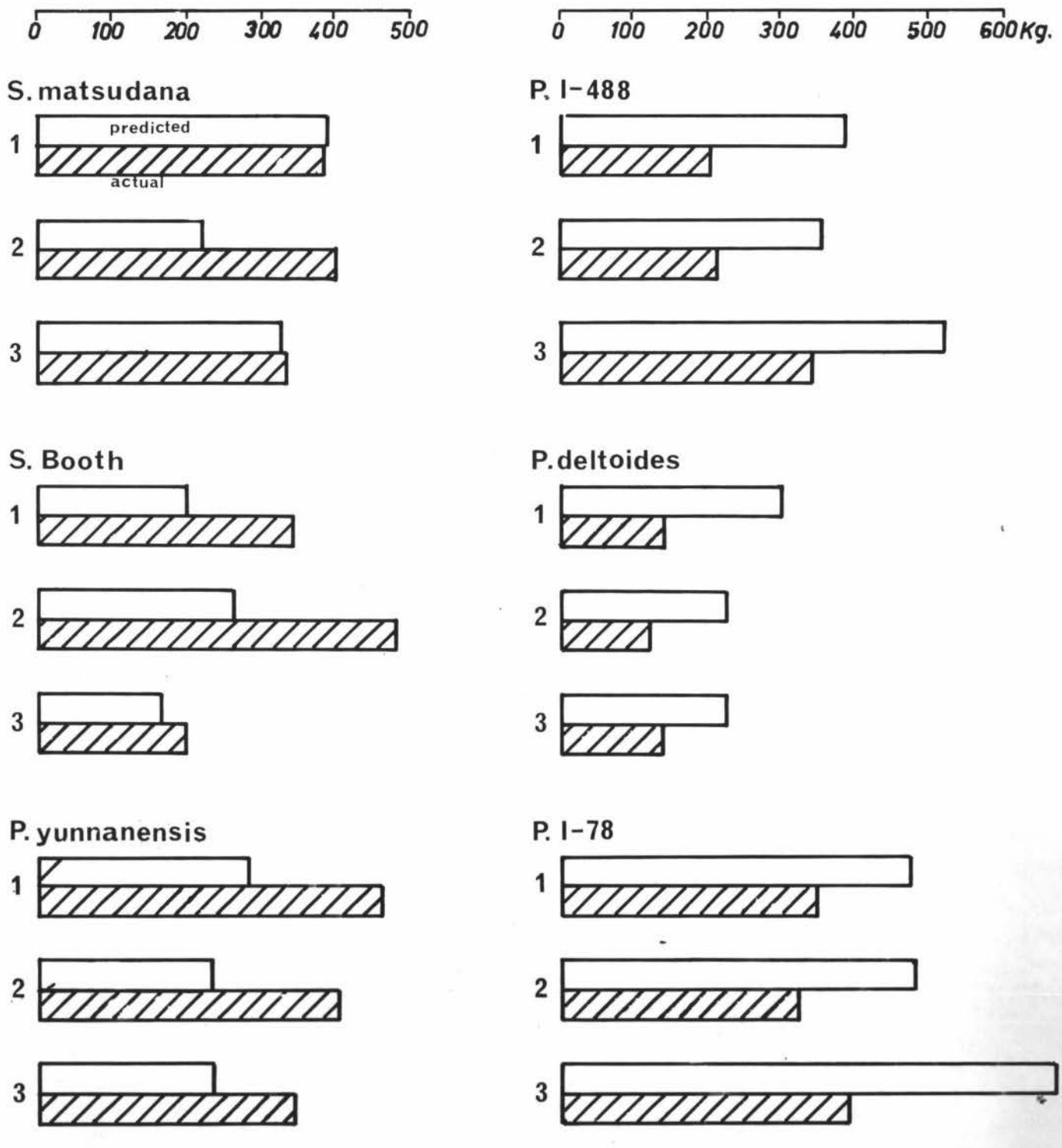
The predicted loads required, and the data used in the calculation, are given in Appendix 13. Fig. 14 shows the predicted and actual loads required to remove the root systems for the fibrous and non-fibrous clones. It can be seen that in the clones with a high percentage of fibrous roots, the measured load was about the same or less than the predicted load required. In the clones with few fibrous roots, the measured loads were considerably less than the predicted loads. This indicates that the fibrous roots contributed substantially to the soil binding capacity of the root systems.

The contribution of the roots greater than 1mm. in diameter is given below for the purpcses of comparison.

P. I488	164%)	
P. deltoides	193%)	non-fibrous
P. I78	163%)	
S. matsudana	84.3)	
S. Booth	63.7)	fibrous
P. yunnanensis	52.6)	

The contribution of roots greater than 1mm. in diameter was considerably over estimated, and this was no doubt due to the fact that all roots did not break at the same time. If allowance is made for this over

Fig. 14 Predicted and actual loads required to remove the root systems



estimation, it appears that in the fibrous clones, the roots greater than 1mm. in diameter contributed less than 50% to the total soil binding capacity.

The criticism that an uneven distribution of the load during removal from the ground may have existed in root systems with a number of large horizontal roots may also apply to the comparison between the predicted and actual loads required. The clones which required higher loads than were predicted to remove the root systems, as well as having more fibrous roots, also had more deeply penetrating roots. It is possible that a more even distribution of the load in the root systems with deeper penetrating roots may have resulted in the higher measured loads. The clones with generally shallower root systems and few fibrous roots all took lower loads to remove the root system than were predicted.

However, it is considered that this effect of load distribution could not account fully for the differences between the fibrous and non-fibrous clones, for the following reasons. Firstly, the very large differences in the actual loads required between the fibrous clones (average of 151% predicted load) and the non-fibrous clones (average of 58% predicted load), whil only a small percentage of the horizontal roots failed to break at the maximum load. Secondly, the actual load measured for P. yunnanensis (average of 192% predicted load) was considerably greater than that of S. matsudana (120% predicted load) even though S. matsudana had a considerably greater number of larger deeper penetrating roots than P. yunnanensis.

As most of the roots broke somewhere along their length during removal from the soil, the variation in the tensile strength of these roots must have had some effect on the soil binding capacity of the root systems. However, the correlation coefficient between the adjusted mean values of the tensile strength of the stele and the root system strength indices is .09. There may be several reasons for the lack of any relationship.

(i) Although the tensile strength of the stele of P. I78 was significantly greater, there was little variation between the other clones in this respect.

(ii) There may be a confounding effect by the variation in the amount of fibrous roots.

(iii) The root system strength indices are based on the load required to remove the root system, divided by the air-dry weight of the roots,

including the cortex. Thus to be strictly accurate, the correlation should be between the root system strength index and the overall tensile strength of the roots, including the cortex.

As there was considerable variation in the ratio of stele to cortex between the clones, this third reason was investigated further. The variation in the overall tensile strength of the roots would be considerably greater than that of the tensile strength of the stele. Thus an estimate of the actual tensile strength of the roots, including the cortex, was calculated for each clone, (Appendix 14) and these figures used in a correlation analysis with the root system strength index. This resulted in a correlation coefficient of .74*. Thus the overall tensile strength of the roots appeared to have a significant effect on soil binding capacity, even though the variation in the tensile strength of the stele apparently had no significant effect.

As the sample size was so small, (n = 6 clones), the relative contributions of the amount of fibrous roots, and the tensile strength of individual roots could not be quantified with any degree of accuracy. However, a multiple regression analysis was carried out (see Appendix 27), and this indicated that these two factors together accounted for 71.3% of the variation in soil binding capacity, the contribution being almost significant at the 5% level.

The standardised partial regression coefficients, indicating the relative importance of each factor, (provided they are not correlated themselves) are :

B1 (overall tensile strength of the roots) = .13
B2 (percent fibrous roots) = .81

The analysis of variance of the multiple regression indicated that there was no significant contribution of either factor to the regression when the factor was placed second in the regression equation. This is probably due to the very small number of samples, and hence few degrees of freedom.

It appears from these results that the amount of fibrous roots in the root system is of most importance in determining the soil binding capacity, although the overall strength of the individual roots, which depends to a large extent on the amount of cortex present, has some effect.

3.6. Seasonal variation in composition, specific gravity, and tensile strength of individual roots

The main purpose of this part of the study was to investigate the effect of any seasonal variation in chemical composition on tensile strength. It was considered that an increase in lignification over the dormant period was possible, which would possibly affect the tensile strength. Specific gravity was also determined, as this was likely to show variation due to the formation of 'earlywood' and 'latewood'. Roots of two clones (P. I488 and S. matsudana), were used in the investigation to determine whether common trends existed.

3.6.1. Chemical composition and specific gravity

The cellulose, hemicellulose and lignin contents of monthly samples of roots of both clones were determined as described in Section 2.4.12. The cellulose contents were determined by hydrolysis to glucose. Results are shown on a percent starch-free dry weight basis in fig. 15 and as the actual amounts of chemical components present per volume of root together with specific gravity in fig. 16.

The seasonal variation in starch content is given in Appendix 15. The hemicellulose contents given are almost certainly less than the actual contents, due to the extraction procedure (see Section 1.8.1) but are included for the purpose of comparison.

The results on a starch free dry weight basis will be discussed first. In both clones cellulose contents were highest in the early part of the year, and in P. I488, were also high in the August and September samples. There were no common trends between the two clones in hemicellulose content, which in P. I488 decreased gradually from a high value in the March samples, and in S. matsudana rose to a peak in the July and August samples. The lignin contents in both clones were highest in the September to February samples. The lignin/cellulose ratios showed highest values in the September to January samples.

The basis assumption in the investigation was that roots sampled at a particular time of the year had developed over a particular period of the year preceding the sampling date. The length of this period no doubt varied with seasonal fluctuations in growth, and this must be taken into account in the interpretation of the results of the variation in composition. Roots examined were all of approximately the same size and were not the

Fig. 15 Seasonal variation in chemical composition
(PERCENT STARCH-FREE DRY WEIGHT)

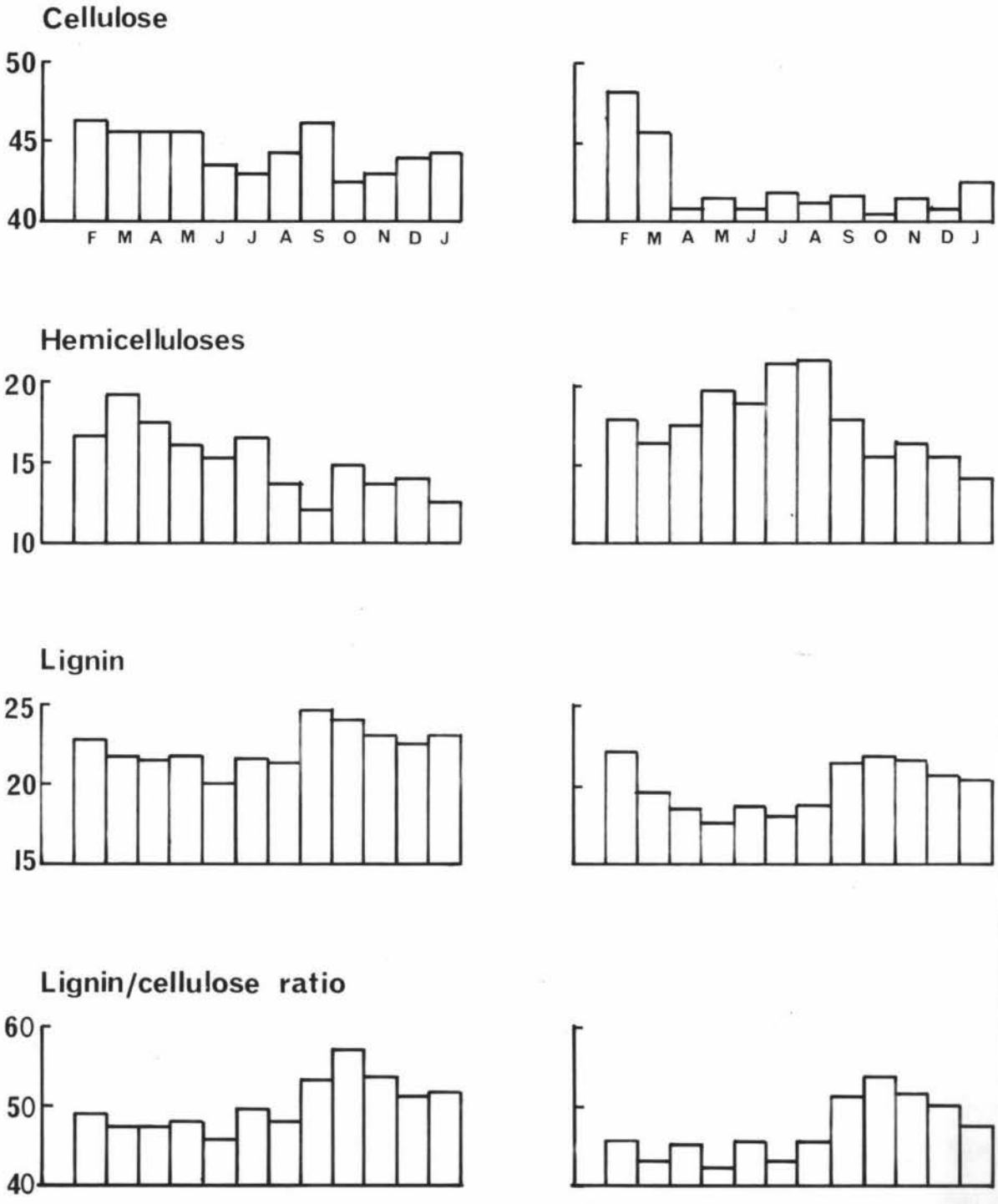
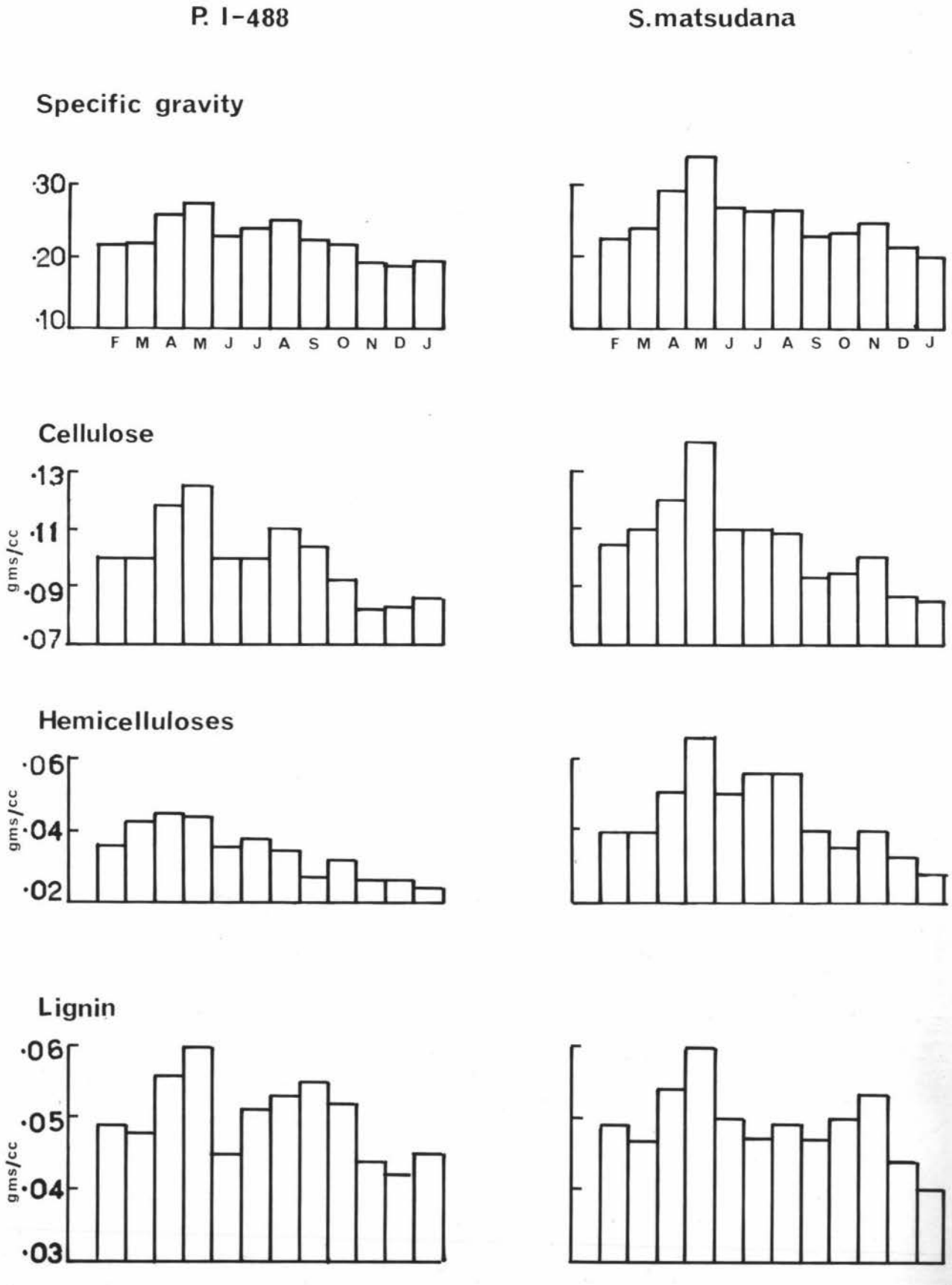


Fig.16 Seasonal variation in specific gravity and actual amounts of chemical components per unit volume of root



"same" roots sampled progressively. Thus roots sampled in February were, of necessity, less than five months old, as the cuttings were planted in August of the preceding year. Roots sampled in August would have developed over a longer period, due to the lack of growth during the winter months. Roots collected during the period September to January contained decreasing amounts of latewood in the inner part of the roots, and increasing amounts of earlywood.

The variation in cellulose content did not appear to be related to earlywood and latewood formation, especially in S. matsudana. The reason for the high cellulose content during the early part of the year in both clones is not obvious. It would be expected that the high lignin concentrations known to exist in the middle lamella (see Section 1.4.3) and the relatively thin secondary wall in these young roots would result in higher lignin and lower cellulose contents during this part of the year.

The roots with the highest lignin contents (September to December samples) consisted mainly of latewood, and had probably developed mostly during the autumn and possibly early winter.

It appears that there was no increase in lignification during these months. The relatively high lignin contents of the roots collected in February could only be explained by the high concentrations of lignin known to exist in the middel lamella, and the thin secondary wall consisting mainly of cellulose (Section 1.4.3). Phloroglucinol tests of the monthly samples showed lignin to be present throughout the stele of the roots in all cases, and there was no observable differences between earlywood and latewood. The middle lamella (and primary wall) stained darker than the secondary wall.

The seasonal variation in the actual amounts of the major chemical components per unti volume of root closely followed the variation in specific gravity, although there was some irregularity in the case of lignin. (see fig. 16). Specific gravity was highest in the April and May samples in both clones. It would be expected that the highest amount of latewood and hence the highest specific gravity would have been present in the August and September samples, just before the new seasons growth began. This apparent anomaly can only be attributed to sampling variation, although care was taken, in selecting roots for investigation, to collect roots from the same depth and position.

3.6.2. Tensile strength

There was considerable seasonal variation in all three measures of tensile strength. Results of individual tests are given in Appendix 11.

The three tensile strength parameters were negatively correlated with the diameter of the stele, and correlation coefficients and regression equations are given in Appendix 19. As there was some variation between monthly samples in the spread of the diameters of the test samples, this correlation between size and strength meant that the means of all the samples tested could not be used for comparisons.

To overcome this, the adjusted means from a covariance analysis were used, with the diameters of the test samples being taken into account. (Appendix 23 and 24). Fig. 17 shows seasonal variation in the tensile strength of the stele, fibre wall strength, and specific tensile strength, based on the adjusted means.

The roots of both clones were strongest in all the tensile strength parameters in the September to November samples. The tensile strength of the stele, and fibre wall strength also showed relatively high values in the March to May samples, while specific strength was lowest during this period.

3.6.3. Relation between seasonal variation in composition, specific gravity, and tensile strength

The correlation coefficients and regression equations between seasonal variation in the tensile strength parameters and composition are given in Appendix 20.

The tensile strength of the stele was negatively correlated with cellulose content (significant in S. matsudana) and positively correlated with the lignin/cellulose ratio. Fibre wall strength was also positively correlated with lignin content and lignin/cellulose ratio. The correlations with cellulose content were not significant. Specific tensile strength was correlated with lignin content (significant at 5% level) and with the lignin/cellulose ratio (significant at 1% level) in both clones. The correlations between all strength parameters and hemicellulose content were generally low and non-significant.

Fig.17 Seasonal variation in tensile strength

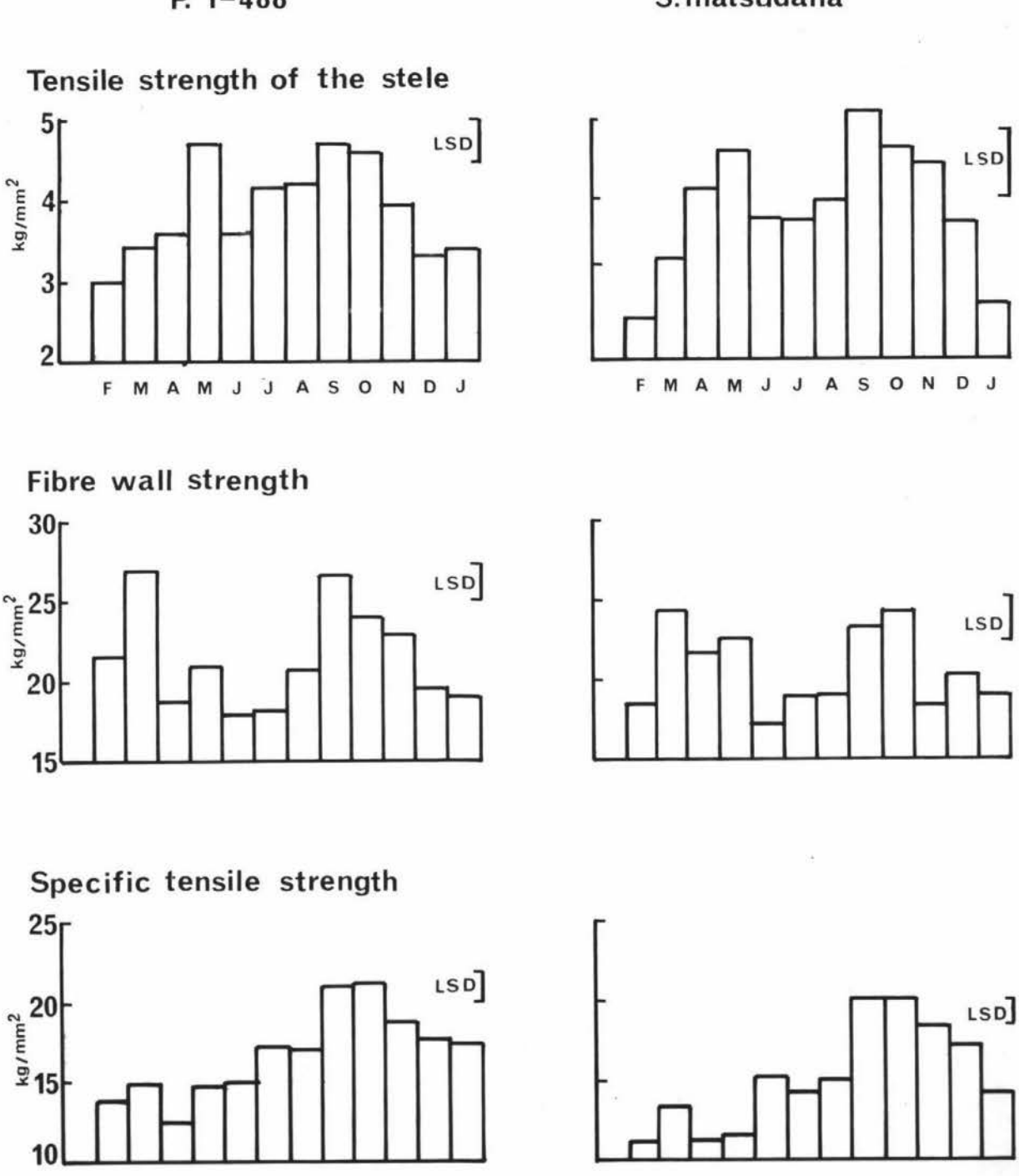


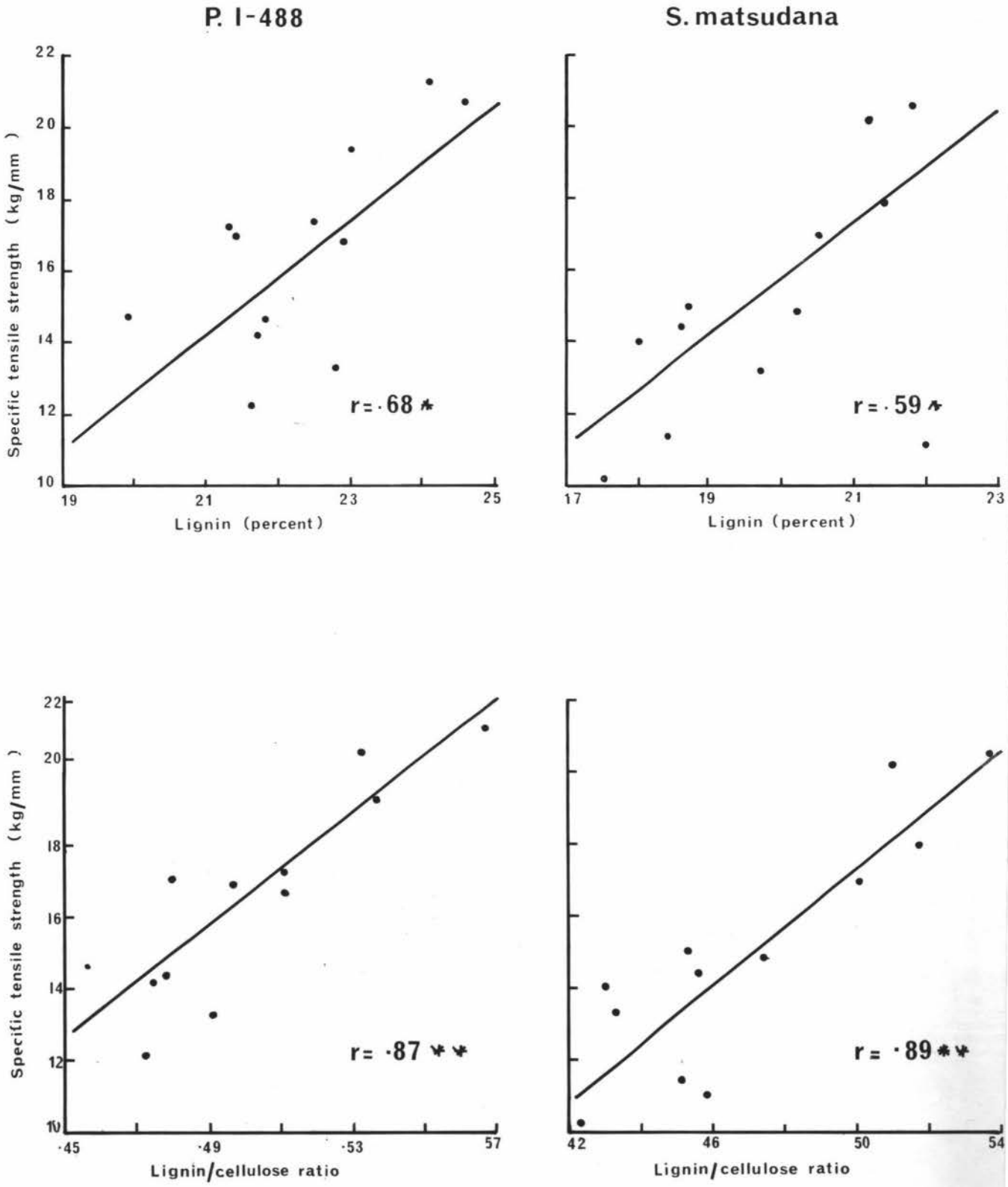
Fig. 18 shows the regressions of specific strength of lignin content and lignin/cellulose ratios for both clones.

The negative correlations of tensile strength with cellulose content were also unusual. In the case of S. matsudana, the correlation is probably exaggerated, due to the relatively high cellulose contents of the February and March samples in comparison with those of samples taken during the remainder of the year.

These aspects will be discussed further in Chapter 4, in relation to previous work.

The correlations and regressions of tensile strength of the stele on the actual amounts of chemical components present, on a weight per unit volume basis, are given in Appendix 21. Only the correlation between the seasonal variation in tensile strength of the stele and the weight of lignin present in P. I488 reached a significant level. In both clones, tensile strength was more highly correlated with lignin content than with cellulose content, showing a similar trend to the correlations with percentage composition

Fig.18 Relation between lignin content, lignin/cellulose ratio and specific tensile strength



CHAPTER 4

D I S C U S S I O N

The main aims of the investigation were to determine :

(1) whether the root systems of several poplar and willow clones varied in soil binding capacity.

(2) what characteristics of the root systems were most important in determining soil binding capacity.

It was shown that there is considerable difference between clones in soil binding capacity, as measured by the load required to pull the root systems vertically from the soil. There were also differences in the morphology of the root systems, and in the anatomy, chemical composition, and tensile strength of individual roots.

The variation in the morphology of the root systems and the characteristics of individual roots, will be discussed first, and then the relationship of these factors with soil binding capacity.

MORPHOLOGY

The root systems of the clones investigated showed considerable variation in morphology, when grown under the same environmental conditions. The form of the root systems ranged from the shallow and non-fibrous type of P. deltoides to the deep root system with many fibrous roots of S. matsudana. In general the poplar clones had root systems with few fibrous roots and large surface roots with a wide lateral spread, while the willow clones had more deeply penetrating roots, with many fibrous roots, but a smaller lateral spread. P. yunnanensis was an exception, showing features of both types of root system. The presence of this degree of variation between clones growing on the same site indicates that the variation is genetic. It would be expected that the variation present in these young trees would persist for several years at least, but may be modified considerably by site conditions. Further work is necessary to determine whether similar variation exists in mature trees.

The variation between clones in the morphology of the root systems agrees in general with the results obtained previously with both poles and stakes (Hathaway, 1970).

INDIVIDUAL ROOTS

It was shown that although there was considerable variation in the tensile strength of roots within a clone, there was little variation in mean tensile strength between clones.

Individual roots of the same clone varied considerably in the three tensile strength parameters, and this was shown to be due to a number of factors.

The variation in the tensile strength of the stele was due mainly to differences in specific gravity (79%). Although the range in specific gravity was only .210 to .260, (clone P. I488), some roots were more than twice as strong as others.

The dependence of the tensile strength of the stele on specific gravity is in agreement with the behaviour of stemwood, where specific gravity is taken as a good indication of strength in general. The only other significant effect of anatomical characteristics on the strength of the stele was that of the area occupied by vessels, a factor closely correlated with specific gravity anyway.

The tensile strength of the stele was understandably correlated with the strength of the fibre walls and specific tensile strength (also a measure of cell wall strength). These strength parameters varied considerably within the clone, and this was shown to be partly due to variation in microfibril angle. This has been shown to occur in stemwood on many occasions (see Section 1.4.3). The smaller the angle between the microfibrils of the S2 wall layer and the long axis of the cell, the greater is the tensile strength. Variation in microfibril angle accounted for only 31% of the variance in fibre wall strength and 19% of the variance in specific tensile strength, and in the case of fibre wall strength, the additional factors of the diameter of the stele accounted for a further 5.4%. This means that other factors not taken into consideration in the investigation must have been important in determining the strength of the cell walls. The only other likely factor is that of variation in chemical composition, which was not studied on an individual root basis.

The effect of the diameter of the stele on the tensile strength parameters in material of the size used is surprising, considering this

effect is usually associated with very small crystalline filaments. However, the effect has been noted previously in roots (Turmania, 1965) and in small wood samples (Sumiya and Sugihana, 1957).

As there was no correlation between microfibril angel, specific gravity, or fibre dimensions, with the diameter of the stele, the effect could not be attributed to any of these factors. Also, when the effect of variation in specific gravity was removed, by utilising specific tensile strength, the correlation was even greater in some clones. The fact that the strength of the cell walls themselves was also related to the diameter of the test sample (highly significant in some clones) indicates that the cause lies at an ultrastructural or molecular level.

The high strength values characteristic of small crystalline filaments such as glass fibres have been attributed to the fact that the probability of structural defects occurring is greater in larger samples (Hearle and Peters, 1963). It is possible that a similar situation exists in cell walls, defects, or "weak links" in the crystalline structure of the cellulose microfibrils being more likely to occur in larger material. Turmania attributed the correlation of tensile strength of roots with diameter to this reason, but thought that the effect disappeared in larger samples due to the increasing lignification of the roots.

The effect may not only be due to the probability of defects in the crystalline structure of cellulose being greater in larger samples. It is possible that in roots, the effect is due to the probability of "weak links" in the bonding between cell wall layers, or in the middle lamella, being greater in larger samples. Such an explanation could also account for the large amount of variation present in the tensile strength of the cell walls of roots of the same clone.

Variation in chemical composition, and the variation in the amount of juvenile wood between small and large diameter samples could possibly explain the phenomenon. However, the proportion of juvenile wood present in the smaller samples was higher, and as juvenile wood is usually weaker than mature wood, under normal conditions, (Panshin and de Zeeuw, 1970), it would be expected that the smaller samples would in general be weaker. The reason may possibly be related to the aspect of lignification. Juvenile wood is known to be lower in cellulose content and higher in lignin content than mature wood. It is possible that as the seasonal variation in fibre

wall strength and specific tensile strength was significantly correlated with the lignin content and lignin/cellulose ratio, that the higher lignin content known to be present in juvenile wood could account for the greater tensile strength of the smaller samples. This will be discussed in more detail with the results of seasonal variation in tensile strength.

If the variation in chemical composition between samples was the cause of the considerable variation in tensile strength then an additional complicating factor would be that of variation caused by seasonal differences in the rate of growth. It was assumed during the study that roots sampled at a particular time during the year had developed over a similar seasonal period. However, it is possible that if some roots grew faster than others, due to local variation in soil conditions, then the slower growing roots could have contained tissues developed at a time during the year different to those of fast growing roots. It has been shown by other workers that early wood and late wood may differ in composition, and that tensile strength is related to composition (see Section 1.4.3).

The variation between clones in the tensile strength of roots was not substantial, although the tensile strength of the stele and specific tensile strength of roots of P. J78 was shown to be significantly greater than that of roots of the other clones. There were no significant differences between clones in fibre wall strength. Because of this lack of significant differences between clones in tensile strength, it was difficult to relate inter-clonal variation in anatomy and composition to tensile strength, and any relationships must be regarded as tentative.

As far as anatomy is concerned there were few differences between clones, and this would be expected from previous work (e.g. Ruggeri, 1963). The anatomy was similar in most respects to that reported for stem wood, taking into consideration the presence of mostly juvenile wood in roots. Fibres were shorter in the roots than those reported for stem wood. The juvenile wood in the centre of the roots consisted of smaller vessels and fibres as would be expected. The most significant feature was the variation in the ratio of stele to cortex. The two willow clones had approximately twice the amount of stele, on a per cross-sectional area of root basis, as the poplar clones (except P. yunnanensis). As the cortex appeared to contribute very little to the overall tensile strength of the roots, this variation in the amount of cortex would be extremely important in accounting for observed variation in tensile strength between clones in the field.

In the preliminary investigation, roots of the willow clones appeared to be considerably greater in tensile strength than poplar roots of the same size.

The estimated overall tensile strength values determined in the investigation were lower than those determined by Turmania (1967) for P. deltoides, but higher than those determined by Schiechtl (1958) for P. nigra. However, they were of a similar order. The difference may easily be due to differences in the environmental conditions under which the trees were grown. Trees grown under more severe conditions would no doubt grow more slowly, and thus the roots would be of greater specific gravity, and hence greater strength. Conversely, faster grown trees, with roots of lower specific gravity, would probably show lower strength values.

The presence of gelatinous fibres in the roots of the willow clones does not appear to have been reported in the literature previously, although it is well known that they are abundant in stem wood. They have been seen in the roots of P. euramericana, (Patel, 1965) and the roots of P. tremuloides (Patel, 1964). None were seen in the roots of the poplar clones used in the present study.

Gelatinous fibres have been reported to be present in stem wood but absent in root wood of many species (Patel, 1964). In general, gelatinous fibres in angiosperms are characteristic of tension wood, and are associated with stems and branches of eccentric form, the tension wood occurring on the upper side of the branches (Wardrop, 1965). This did not appear to be the case in the roots examined and the gelatinous fibres were evenly distributed around the pith. This was also noticed by Patel (1964), in the roots of the species examined by him.

The formation of tension wood may be induced experimentally by applied stresses, or auxin treatment, but the functional significance is not clear. It is generally thought that reaction wood is formed in the branch or stem to resist gravitational or other stresses acting on the tree, or as a mechanism for growth movement (Wardrop, 1965). In roots, the gravitational force would not create any tension in the root, as it is supported by soil. Two other forces are possibly acting on the root during development; the pressure of the soil as the root expands, and the tensile stress created in the root as a result of wind acting on the shoot. The presence of gelatinous fibres in the roots of the Salix clones is possibly due to either of these factors.

The roots of the clones examined were shown to differ quite markedly in chemical composition and this variation was somewhat greater than would be expected from the literature on stem wood (e.g. Anon, 1958). Some of this variation was possibly due to errors in the determinations, as the figures given are the means of only two determinations per clone. However, as the determinations were seldom greater than 2% different, considerable variation in the composition of the roots must exist.

It is of interest that inter-clonal variation in fibre wall strength was significantly correlated with Cross and Bevan cellulose content, but not significantly with cellulose as determined by hydrolysis to glucose. If these correlations are accurate, this would indicate that the non-cellulosic polysaccharides included in the Cross and Bevan determinations have a function in determining the tensile strength of the roots.

The study of inter-clonal variation in the stress/strain behaviour of the roots showed significant differences between several clones in Young's modulus and ultimate strain. Young's modulus was shown to be significantly correlated with the Cross and Bevan cellulose content and negatively correlated with the lignin/cellulose ratio, indicating that roots of clones with higher cellulose contents and lower lignin/cellulose ratios extended less before breaking. This may be due to the larger force required to shift a greater number of cellulose chains into alignment with the direction of principle stress, in order that chain slippage and bond breakage may occur.

The shape of the stress/strain curves was considerably different to those normally obtained with stem wood (e.g. Jayne, 1960).

This was possibly due to a large proportion of juvenile wood present in the roots, and the very low specific gravities of the samples.

Soil Binding Capacity

The results show that there was considerable variation between clones in soil binding capacity, when this was expressed as the load required to remove the root systems vertically from the soil per unit weight of root material. It is not proposed that this measure is an accurate determination of soil binding capacity, but at least gives some indication of the tenacity with which the roots are attached to the soil.

This measure of soil binding capacity appeared to depend largely on the amount of fibrous roots in the root system, although morphological features, such as the depth of the major roots, may have had some effect.

The variation in overall tensile strength of individual roots appeared to have less effect than the amount of fibrous roots, under the conditions of the investigation. However, the relative importance of these two factors is not absolutely clear, and further work needs to be carried out under varying soil types and soil moisture conditions. Although the investigation provided a quantitative measure of the importance of the amount of fibrous roots, in different soil conditions, this may not apply.

When tension is applied to a root in a soil mass, the major force acting to resist the movement of the root through the soil is that of friction between the root surface and the soil particles. This could possibly also be termed the shear stress, or yield stress. Its magnitude will depend on both soil factors and root factors.

a) Soil Factors :

Of most importance will be the consistence of the soil, which is defined as "the inherent qualities of soil material that are expressed by the resistance to deformation or rupture" (Taylor and Pohlen, 1962). As roots invariably have irregularities and branches along their length, the movement of the root through the soil by an applied force will require the soil to be compressed or displaced to a certain extent. As soil consistence varies directly with the moisture content of a soil, being high in a dry soil and low in a wet soil (Kohnke, 1968), the moisture content of the soil will directly affect the shear stress. The coefficient of friction of the soil material will influence the shear stress and this also varies with soil moisture content.

The shear stress will also be influenced by the compaction and bulk weight of the soil.

b) Root Factors :

The magnitude of the frictional force will also depend on the area of contact between the root and the soil, and thus the amount of fibrous roots will be important. The morphology of the root will also have an effect. Irregularities and branches along the root will cause the soil to be deformed or compressed as tension is applied.

If the frictional force below a given point is greater than the load required to break the root at that point, with increasing tension, the root will break. Within each root, or its branches, there will occur a critical point of failure, above which the root is strong enough to resist the load required to overcome the frictional force occurring below the point. The position of this point will depend to a large extent on the soil physical properties at the time and situation under consideration. For example, in a soil with a very low consistence, and high moisture content, the frictional force will be so small that the entire root and its branches could be pulled through the soil without breaking. At the other extreme, the soil could be so compressed and unyielding that the load required to overcome the frictional force would be so high that the root may break near its base. However, although the two factors are inseparable, under high moisture content, and low soil consistence, which are the conditions of maximum soil instability, it would appear to be the area of roots in contact with the soil, and hence the amount of fibrous roots that will be of most importance.

Seasonal variation in the tensile strength of roots

The chemical composition, specific gravity, and tensile strength of roots formed at different times during the year were shown to vary considerably. This was almost certainly due to the varying rate of growth occurring at different times during the year, resulting in the formation of early wood and late wood. These tissues were not clearly defined, and there was a gradual transition from large fibres and vessels in the early wood to smaller cells in the late wood.

The variation in specific gravity followed the pattern generally found in stem wood, with highest values occurring during the winter period. However, the highest values were found to occur in the samples collected in May, while it would be expected that specific gravity would increase or at least remain constant throughout the winter until new growth commenced in the spring. The actual specific gravity determinations of the samples were corrected for starch content which was quite considerable during the winter months, and it was assumed that the total starch content of the samples was taken into consideration. However, it was possible that the method of determination did not measure the total amount of starch present even though repeat extractions of the same samples indicated no further starch to be present. Some starch may have been tightly bound inside fibres

that were not ruptured by the extraction procedure. This could have accounted for the elevated specific gravity figures of the April and May samples, which was also the period of highest starch content.

The cellulose content of the roots did not appear to be directly related to the presence of early wood or latewood, although that of roots of P. I488 showed generally lower values in the June to November samples, which consisted mainly of latewood.

Thus the situation found in these roots does not seem to follow the general pattern reported for stem wood, where the cellulose content of latewood is usually greater than that for early wood (Section 1.4.3). The reason for this may be that the wood in the roots was essentially juvenile wood, being only a few months old. The composition and structure of juvenile wood may be considerably different from that of mature wood. In stems, wood close to the pith is distinctly different to wood near the bark, and also the cellulose content of wood from near the pith is reported to be well below the level in mature wood. The juvenile period may last 5-20 years (Panshin and de Zeeuw, 1970). This means that the comparisons between the composition of mature stem wood and juvenile root would are not strictly valid.

In stem wood it is usually reported that early wood is higher in lignin content and lower in cellulose content than late wood (Panshin and de Zeeuw, 1970; Wardrop, 1965; Wise, 1944). (See Section 1.4.3). The variation is lignin content of both clones showed a similar trend, with lowest values in the May, June and July samples and highest values in September and October. This indicates that there was an increase in lignin content over the winter period, which decreased as the amount of early wood increased.

The process of lignification occurs from some time after the formation of the cell by the cambium, until the death of the cell (Northcote, 1958; Wardrop, 1957). According to Lobzanidze, 1958, lignification of earlywood cells of many species was not complete until eleven weeks after cambial growth began. As the roots used in the present study were only up to 6 months old, a large proportion of the cells would not be completely lignified at the time cambial growth slowed down in the autumn. If lignification continued in these cells after the growth was reduced or

stopped, this may have accounted for the increased lignin content of the roots in winter. The decrease in lignin content in the spring was possibly due to a rapid increase in wall material consisting mainly of cellulose, and the lag before lignification of the cells was complete. The high lignin content of earlywood of stems is often attributed to the high proportion of the cell walls of earlywood that is middle lamella and primary wall (e.g. Wise, 1944). The thickness of the cell walls in these roots did not show great variation, except those in the outer 5-10 rows of cells of the samples collected in the winter were slightly thicker. Thus the variation in wall thickness was not likely to affect the proportion of middle lamella and primary wall present to any great extent, and this could explain the anomaly with results obtained from stemwood.

The tensile strength of the stele of the roots was shown to vary considerably with the season, and was correlated with variation in the specific gravity of the roots although not at a significant level. The lack of significance could be due to the possibly elevated specific gravity figures resulting for the April and May samples, as discussed above. However, the tensile strength of the stele showed two peaks, one in May and the other in September. The peaks in May correspond with the high specific gravity figures for this month, and this means that the high specific gravity figures for May may be real. Conversely, the peaks in May appear incongruous when the overall seasonal variation is studied, and do not fit the general pattern. It is possible that as the months preceeding May when these roots formed were quite dry the rate of growth slowed sufficiently to cause an increase in the specific gravity. The rate of diameter growth of the roots may have increased with higher soil moisture levels in Autumn, resulting in larger cells with lower specific gravities (even though shoot growth stopped in March and April, it is known that root growth proceeds longer into the Autumn than shoot growth (Kolowski, 1971). Alternatively, it is possible that sampling variation caused this apparent anomaly.

The variations in the tensile strength of the roots are almost certainly of secondary importance from an adaptation aspect and are the result of seasonal variation in growth rate rather than direct adaptations to such environmental influences as stresses within the root systems as a result of wind forces acting on the shoot.

The significant correlations between the strength of the cell walls (as measured by fibre wall strength and specific tensile strength) and the lignin content and lignin/cellulose ratio of the roots were unexpected when

the work on stemwood is considered. In stemwood tensile strength has often been correlated with the cellulose content of the test sample and the compressive strength with the lignin content (see Section 1.4.4). The tensile properties of small wood samples have generally been studied using air-dry material (e.g. Barefoot, 1965; Grozditz and Ifju, 1969; Jayne, 1966; Van Vliet, 1959) and tensile strength has been correlated with cellulose content rather than lignin content. Grozditz and Ifju (1969) concluded that lignification alone does not appear to influence the tensile strength. Ifju, (1964) found that the degree of polymenisation of cellulose had less affect on tensile strength at a high moisture content than at a low moisture content. This would indicate that cellulose content was less important at a high moisture content. Klauditz et al (1947) found that lignin seemed to affect strength properties more at high moisture contents, and thought that lignin protects hydrophilic substances that can bear loads when dry but not when wet.

It is thus possible that lignin is important in determining tensile strength at high moisture contents. As the tensile strength of the roots used in the present study was determined using material above the fibre saturation point the results would support this hypothesis. According to Ifju (1964) water diminishes cohesion between microfibrils and the molecular bundles in wood, and the function of lignin is to reinforce the cellulose microfibrils. It appears from this study that it's presence may protect the bending between microfibrils from breakage by water molecules, especially under saturated conditions.

Practical significance of the study

Of the most significance as far as soil conservation work is concerned is that the clones used in the study showed considerable variation in soil binding capacity, if the load required to remove the root system vertically from the soil is an acceptable measure.

There was a large amount of variation between clones in the amount of fibrous roots present, and this appeared to be very important in determining the soil binding capacity of the root systems. The amount of variation present indicated that there is considerable scope for the selection of improved varieties.

Although the variation between clones in the tensile strength of the stele did not appear to have any great effect on soil binding capacity, it is possible that it could be important in the selection of superior clones from those with a similar morphology. The variation in the amount of stele present was much greater and as this is an important factor in determining the overall tensile strength of the root, would be one of the main factors to be considered during selection.

It is probably not now necessary to conduct actual tensile tests of roots to determine which clones are likely to have roots of greater tensile strength. The preparation of test samples for testing is very time consuming, and to obtain accurate strength values, expensive equipment is necessary. The results of the study show that the main factor effecting the tensile strength of the stele is specific gravity, and this can be determined quite simply with a minimum of equipment and time. The amount of stele present in the roots is also easily measured, and by using the results of the tensile tests given, a good indication of the overall tensile strength may be obtained.

The variation present in the morphology of the root systems indicates that is may be possible to select trees with particular types of root systems for particular erosion control problems. For example, deeper rooting clones could be more useful when a slip plane exists several feet below the soil surface. However, further work must be carried out to determine whether the morphological variation present in these young trees continues in older trees.

Future Work

From the results of the present study, a number of questions arise which require further investigation.

Firstly, is the need to establish whether the load required to pull the root systems vertically from the ground is an accurate measure of soil binding capacity. An alternative method would be to measure the load required to pull individual roots from the soil, the load being applied parallel to the axis of the root. This would overcome any confounding due to the angle at which the roots of a complete root system penetrate the soil. The results could then be compared with those obtained by measuring the vertical load.

It would also be desirable to determine under what soil conditions the amount of fibrous roots in the root system is most important, relative to the variation in the strength of individual roots. Both of these questions could be investigated by growing individual roots from a cutting into long containers filled with a range of soil types. When the root had grown to the end of the container it could then be cut from the tree, and the container removed to the laboratory for the measurement of soil binding capacity. This would overcome the difficulty of setting up accurate load measuring equipment in the field, and also would enable the soil binding capacity of roots of a particular clone to be determined over a range of predetermined soil moisture conditions, simply by wetting or drying the soil in the containers. It would also enable all the fibrous roots to be recovered with a minimum of effort.

The function of trees planted for soil conservation purposes is often to prevent surface slipping where the upper soil layers move downhill on a shear plane a short distance below the soil surface. To determine whether the results of the present investigation apply in this situation, it would be desirable to simulate the situation by measuring the loads required to move blocks of soil planted with trees of various clones across a shear plane. Preliminary investigations indicate that this type of experiment may be practicable, and a pilot trial has been laid down, using the same clones as in the present study. The shear strength of the soil blocks with and without roots will be measured after one growing season.

In a wider sense, the question still to be answered concerning the soil binding capacity of root systems is; "What is most important, the mechanical reinforcing action of the root systems, or the reduction in soil moisture levels by evapotranspiration in the growing season?". As no data is available as yet on the rates of transpiration of poplars and willows growing in New Zealand, and the reduction in soil moisture that can be expected, this is a difficult question. Various methods of estimating transpiration are available, and it should not be too difficult to get some data on this aspect. Possibly, a long term field experiment may provide some answers. A uniform slope that is subject to slipping and slumping could be planted in blocks with and without trees, and soil moisture determinations made through the year to determine the reduction in soil moisture that occurs in the areas planted with trees. However, a problem with this type of experiment is to obtain a large enough area of uniform soil type, slope, and aspect.

CHAPTER 5

CONCLUSIONS

1) There is considerable variation in the morphology of the root systems of one year old poplars and willows when grown under the same environmental conditions. This variation is mainly in the depth of the root systems, and in the amount of fibrous roots present. Under the particular conditions of the investigation, the willow clones are generally deeper rooting, and the root systems have a greater amount of fibrous roots than the poplars, which have more large horizontal roots near the surface, and few fibrous roots. There are exceptions to this generalization, as in P. yunnanensis, with large horizontal roots and a number of deeper penetrating roots as well. This clone also has a considerable amount of fibrous roots.

2) Individual roots of the same clone vary considerably in tensile strength. The variation in the tensile strength of the stele is due largely to differences in specific gravity. The variation in cell wall strength is due partly to variation in microfibril angle.

3) In general, there is little variation between clones in the tensile strength of the stele, fibre wall strength, or specific tensile strength. However, roots of P. 178 are significantly greater in the tensile strength of the stele and specific tensile strength. Although inter-clonal variation in the tensile strength parameters was significantly correlated with anatomy and chemical composition in some features, the lack of significant differences in tensile strength between clones indicates that these relationships may not be accurate.

   The varying amounts of cortex present in the roots is likely to cause quite large differences in overall tensile strength, and this is likely to be the major cause of the differences in tensile strength noticeable in the field.

   There is some variation between clones in Young's modulus depending on the cellulose content of the roots, but little difference in strain at failure.

4) The root systems vary considerably in soil binding capacity, as measured by the load required to pull the root systems vertically from the soil, and this variation is caused mainly by the variation in the amount of fibrous roots present. Of the clones studied, S. matsudana, S. Booth, and P. yunnanensis have the greatest amount of fibrous roots, and are the highest in soil binding capacity for their size.

The variation in the tensile strength of the stele of individual roots has little effect on the soil binding capacity, but the estimated overall tensile strength of the roots, where the effect of the amount of cortex present is taken into account, has some effect.

5) Tensile testing is not now necessary to determine differences between clones in the tensile strength of the roots. There is little variation in the tensile strength of the cell walls, so from the specific gravity of the stele, and the amount of cortex present, a good indication of the overall strength of the root can now be obtained.

6) There is considerable seasonal variation in the tensile strength of individual roots, which are strongest during the winter period. Variation in the tensile strength of the stele is caused mainly by differences in specific gravity resulting from varying rates of growth. Seasonal variation in fibre wall strength and specific tensile strength appears to be correlated with lignin content and the lignin/cellulose ratio, and lignin appears to have an important role in protecting hydrophilic bonds between cellulose microfibrils in saturated samples.

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LIST OF APPENDICES

APPENDIX 1

Poplar and willow clones used in the investigation

The following briefly outlines the characteristics of the clones used in the investigation, and their use in soil conservation in N.Z.

A) Poplars

1. Populus x euramericana (Dode) Guinier cv. 'I 78'
(Section Aigeiros)

This is a hybrid between the European P. nigra, and the North American P. deltoides, and as a result of its vigorous growth and good form, has been planted in many countries. It is the most widely used poplar for soil conservation planting in N.Z.

2. P. x euramericana (Dode) Guinier cv. 'I 488'
(Section Aigeiros)

This is again a black hybrid clone of unknown parentage, selected in Italy, and introduced into N.Z. in 1960. It is not as widely used as P. I 78 as yet, but shows very good growth and excellent form in many districts.

3. P. deltoides Marsh cv. 'A 60/129'
(Section Aigeiros)

This is a Texas clone of the North American P. deltoides, and was chosen to be representative of the species. It was introduced into N.Z. in the early 1960's, and is planted to a limited extent in the North Island. An old clone of P. deltoides has been planted in N.Z. for many years but this is now being phased out.

4. P. yunnanensis (Dode)
(Section Tacamahaca)

This is representative of the balsam poplars, which are less site demanding than the Aigeiros poplars. P. yunnanensis is grown throughout the country, and is valuable as a soil conservation tree because it can tolerate drier sites and is fairly resistant to damage by opossums.

B) Willows

Salix matsudana Koidz.

This is a tree willow, and being of vigorous growth and upright habit, is being increasingly used in soil conservation work. It was introduced into N.Z. about 20 years ago, and in this study, was chosen to be representative of the tree willows.

S. purpurea L. cv. Booth

This is one of the osiers, which are shrubby, multiple stemmed willows, and was chosen in this study to be representative of these lower growing willows. It is the most extensively used of the lower growing willows in N.Z., and this is due to its greater vigour than related clones, and to its opossum resistant foliage.

APPENDIX 2

Accuracy of anatomical measurements

1. Fibre wall area (percent of total cross-section area)

To determine the number of determinations required to obtain the desired accuracy, the grid was placed in all possible positions over a typical section, a total of 250, and thus 25,000 determinations of fibre wall or otherwise were made. The mean percent fibre wall area based on these 25,000 determinations was 28.6%. When the grid was placed in 50 positions at regular intervals over the section, involving 5,000 determinations, the mean was 29.3%. Thus, the error involved was less than 2.5%. This was considered to be satisfactory for the purpose.

2. Vessel area

Because it was possible to use a lower magnification, there was less variation in the results from each grid. When the grid was placed in all possible positions over the section (25,000 determinations), the mean was 47.3%. When placed in 25 positions evenly spread over the section (2,500 determinations), the mean was 48.5%, and thus the error involved was 1.7%.

3. Fibre length

100 fibres of each of 5 slide preparations of fibres of P.178 were measured, and the following mean fibre lengths were obtained.

Slide	1.	801μ
	2.	821μ
	3.	790μ
	4.	797μ
	5.	824μ

The maximum error was thus 2.0%. The typical standard error of fibre lengths was approximately 30 microns.

4. Fibre width

Measurements of 100 fibres of each of 5 slide preparations of P.178 gave the following mean fibre widths.

Slide	1.	21.8
	2.	21.7
	3.	22.0
	4.	21.3
	5.	21.3
overall mean		21.6

The maximum error involved was thus 1.45%.

5. Percent parenchyma and rays

As the same magnification as that used in the determination of vessel area was used it was assumed that the same accuracy would occur, and the measurement was made from 25 grid positions evenly spaced over the section.

APPENDIX 3

Moisture content of test samples after various periods of soaking

To determine what soaking period was required to ensure that the moisture content of the test samples was above fibre saturation point, groups of 10 test samples were immersed in water for the following periods, and the moisture content determined gravimetrically.

Length of soaking period	% Moisture content	Standard deviation
30 mins	45.6	4.0
1½ hrs	60.0	5.2
4 hrs	66.4	4.2
24 hrs	75.6	2.2

As the fibre saturation point is between 25% and 30% moisture content, a soaking period of one hour was considered adequate to ensure the test samples were above fibre saturation point right through.

APPENDIX 4

Effect of rate of extension during testing on tensile strength of roots

To determine whether the rate of extension during testing had any effect on the tensile strength of the roots, 10 paired samples of roots of S. matsudana were tested at crosshead speeds of .05 cm/min. and 20 cm/min. These speeds represented sample extension rates of 2.5% and 1000% elongation per minute respectively.

Each pair of test samples was prepared from adjoining sections of the same root, and were 2cm. in length between the blocks. This procedure minimised the effect of any anatomical and chemical variation between samples. Tensile strength was calculated on a total cross-sectional area basis, and results are given below.

	Tensile strength at crosshead speed of	
sample no.	.05 cm/min.	20 cm/min.
1	3.50	4.52
2	3.22	3.79
3	3.67	3.54
4	3.34	3.27
5	4.35	3.66
6	3.56	3.18
7	4.71	3.54
8	4.78	4.50
9	3.87	3.59
10	4.21	4.60
means	3.87	3.82

Although there was some variation in tensile strength of samples of the same root tested at different extension rates, there was no pattern to the variation, and the analysis of variance (Appendix 16), showed that the means were not significantly different.

APPENDIX 5

Analytical methods

1. Determination of extractive content

A 4.5g. sample of material, ground to pass a 40 mesh sieve, and of known moisture content, was extracted in a Soxhlet extraction apparatus for 4 hours each with 95% ethanol and a 1:2 mixture of ethanol and benzene. The material was then washed with distilled water twice, sucked dry, and left overnight to dry out completely. After removal from the extraction thimble, the material was reweighed and a sample taken to determine the percent dry weight. The extractive content was calculated as the loss in oven-dry weight due to the extraction procedure.

2. Determination of hemicellulose and cellulose contents by hydrolysis to simple sugars

From the ground material, a 1g. sample was taken for the determination of moisture content, and a 0.5g. sample for the analysis. The 0.5g. sample was extracted with ethanol and ethanol benzene as described above, and the material in the extraction thimble sucked as dry as possible and left overnight to dry out completely. After removal from the thimble, the sample was placed in a 500ml. flask with 200mls. of 5% H_2SO_4, and boiled for 2 hours under reflux. It was then filtered through a No.1 filter paper covered with a layer of asbestos (suitably treated - see below) in a Buchner funnel, and the filtrate made up to 250mls. The filtrate was assumed to contain the major part of the non-structural polysaccharides (hemicelluloses) hydrolysed to simple sugars, and the amount was determined by the method of Nelson (1944), (see below).

The residue was dried by rinsing with ethanol, scraped off the filter paper together with the asbestos, and left in a warm place overnight to dry out completely. The sample was then placed in a beaker with 10mls. of 72% H_2SO_4, and left for 2 hours with occasional stirring. This mixture was diluted with 330mls. of distilled water to a 3% concentration of H_2SO_4, transferred to a 1000ml. flask, and refluxed for 2 hours. It was then filtered through a Gooch cricible covered with a layer of asbestos, and the filtrate made up to 500mls. The filtrate was used for the determination of the cellulose content of the sample, by determining the amount of glucose present using Nelson's method.

Nelson's method for the determination of simple sugars

Reagents :

1. Copper reagent A - 25g. Na_2CO_3 (anhydrous)
   25g. Rochelle salt, 20g. $NaHCO_3$, and 200g. Na_2SO_4 (anhydrous) dissolved in about 800mls. of water and made up to 1 litre.
2. Copper reagent B - 15% $CuSO_4 \cdot 5H_2O$ containing one or two drops of conc. H_2SO_4 per 100mls.
3. Copper reagent C - Just before use filter 25mls. of Reagent A, add 1ml. of Reagent B, and shake.
4. Arsenomolybdate colour reagent - Dissolve 21g. ammonium molybdate in 450mls. of distilled water, add 21mls. conc. H_2SO_4, mix, add 3g. $Na_2HA_5O_4 \cdot 7H_2O$ dissolved in 25mls. water, mix, and incubate at 37°C. for 24-48 hours.

Method

The filtrate was prepared by placing a 10ml. aliquot with 2 drops of phenolpthalein in a 50ml. volumetric flask, and neutralising with 5N NaOH, then 2N HCl and finally 0.1N NaOH.

For the determination of sugar in the filtrate, 1ml. of the neutralised solution was placed in a 25ml. graduated test tube, together with 1ml. of Reagent C. These solutions were mixed, the test tube covered with aluminium foil, and heated in a boiling water bath for 20 minutes. After cooling, 1ml. of the arsenomolybdate solution was added, mixed until all gases were expelled, and made up to 25mls. The absorbance was read at 520mμ against a blank prepared by using distilled water instead of the filtrate. The value found for the blank was subtracted from the value found for the filtrate. Eight sugar samples were run simultaneously.

Calculation of sugar contents after hydrolysis

The amount of sugar present was calculated from a reference curve of sugar content against absorbance. The reference curve was obtained from the absorbance of 5 standard solutions of glucose. These were prepared in concentrations necessary to supply the quantities required in the 1ml. aliquot covering the range of 0-200mg.

To obtain the amounts of hemicelluloses and cellulose present in the original sample, it was necessary to correct for loss on hydrolysis.

The factors recommended by Saeman et al (1954) were used (Cellulose 2.6%, Hemicellulose 8.8%).

As there was a considerable amount of starch present in many of the samples, and starch is also hydrolysed to simple sugars by weak acids, the hemicellulose content above was due partly to the starch content of the material. Thus to obtain a better indication of the hemicellulose content, the starch content was determined separately (described below), and the hemicellulose content determined by subtraction. However, the hemicellulose contents could not be relied upon as being accurate, as these compounds are not hydrolysed quantitatively to simple sugars and results were only suitable for comparitive purposes.

3. Determination of "Cross and Bevan" cellulose

The semi-micro method of Watson (1962) was followed.

Reagents :

1. Chlorine water, approximately 0.16N, freshly prepared each day.
2. Sulphurous acid, approximately 0.16N.
3. Sodium sulphite, 20g. per litre of Na_2SO_3 in water.

Method

An accurately weighed 0.4 - 0.5g. sample of extractive free root material (milled to pass a 40 mesh sieve) was placed in a tared sintered glass crucible of G2 porosity. The oven-dry weight factor was calculated from a duplicate sample. The crucible was placed in the neck of a filter flask, and partly filled with chlorine water. The material was chlorinated for 15 minutes using applied suction to ensure that 50mls. of chlorine water passed through the crucible. At the end of the 15 minute period the chlorination was stopped by the addition of 10-15mls of sulphurous acid, the sample filtered, washed twice with cold water, and sucked dry. The crucible was then placed in a beaker half-filled with sodium sulphite solution, covered by a watch-glass, and placed in a boiling water bath for 30 minutes. It was then transferred to the filter flask, filtered and washed twice with hot water and twice with cold water. The chlorination cycle was repeated several times, reducing the chlorination period to 10, 5, and 3 minute periods, and then by 1 minute periods until no colouration was obtained on the addition of sodium sulphite. At this point the crucible was filtered, washed and sucked dry as before, and then half

filled with distilled water and heated in the water bath for 30 minutes. It was then filtered and washed successively with 30mls. hot water, 20mls. cold water, 20mls. 0.1% ammonia, 20mls. 1% acetic acid, 20mls. cold water, 50mls. hot water, 20mls. ethanol, and 20mls. ether. After oven-drying for 2½ hours at 105°C. the crucible was reweighed.

Calculation

$$\% \text{ "C + B" cellulose} = \frac{\text{wt. of crucible + residue - wt. of crucible}}{\text{oven-dry weight of sample}} \times 100$$

4. Lignin

After the hemicellulose and cellulose fraction had been removed by acid hydrolysis, as described above (section 2) the crucible, together with the residue, was dried overnight at 105°C, allowed to cool for 10 minutes in a dessicator, and weighed. It was then ashed for 3 hours at 500°C., allowed to cool in a dessicator for 15 minutes and reweighed. The difference in weight was taken as the ash-free lignin content of the sample.

Preparation of asbestos for use in Gooch crucibles

The asbestos used in the above procedures was treated before use with conc. H_2SO_4 for 2 hours, washed to remove fine particles, and ashed at 800°C for 16 hours.

5. Starch

Reagents :

perchloric acid	(7.2M)
potassium iodide	(10% w/v)
potassium iodate	(0.01 N)

Method

An accurately weighed 0.4g. sample of root material (ground as finely as possible with the available grinder) was placed in a glass mortar with a close fitting pestle, together with 4.7mls. of perchloric acid. The oven-dry weight factor of the material was determined from a duplicate sample. The mixture was allowed to react for 10 minutes and ground with the pestle for 10-20 seconds each minute. The contents were then transferred to a 50ml. volumetric flask and brought to volume with distilled water. The solution was centrifuged, and a 1ml. aliquot together with 4mls. of water placed in a 50ml. volumetric flask, a drop of phenolphthalein added and the solution made alkaline with 2N NaOH. Acetic acid (2N) was added until the colour was discharged, and then a further 2.5mls. 5mls. of potassium iodate and 0.5mls. potassium iodide were added, and the colour

allowed to develop for 15 minutes. The solution was brought to volume and the absorbance measured at 650 mμ with a blank prepared without starch as zero.

A standard reference curve of starch concentration against absorbance was set up using potato starch of known moisture content. Weighed quantities of starch from .05g. to 1g. were treated according to the above procedure to construct the reference curve, which was linear, and passed through the origin.

Due to the difference ratio of amylose to amylopectic in potato starch compared with wood starch, and the fact that the iodine method depends on the reaction of the amylose in the starch with iodine, the weight of potato starch was then converted to the corresponding weight of wood starch by the factor of 25.5/23.2, as recommended by Humphreys and Kelly (1961).

APPENDIX 6

Load required to remove each of 10 trees per clone vertically from the ground, measured in kg.

Tree No.	P. yunnanensis	S. Booth	S. Matsudana	P. deltoides	P. I488	P. 178
1.	364	227	386	136	205	386
2.	364	318	352	114	114	295
3.	455	341	398	68	227	341
4.	364	239	375	114	227	318
5.	398	477	295	114	91	386
6.	364	182	364	132	182	250
7.	295	193	329	79	182	386
8.	273	159	365	152	341	318
9.	295	170	365	91	273	330
10.	341	182	432	102	250	364

Analysis of variance

Source of variation	ss	df	Ms	F
Clones	509399	5	101879	25.5 **
Blocks	22380.8	9	2486.7	.62 NS
Residual	179338	45	3985.3	
Total	711119	59		

APPENDIX 7

Root system strength index (load/air dry weight of roots) of the 3 trees per clone selected as having typical root systems

Clone	Root system strength index		
	Tree No.		
	1	2	3
S. matsudana	7.15	11.30	6.81
S. Booth	6.41	8.06	5.12
P. yunnanensis	6.10	5.13	5.96
P. I488	3.45	2.39	4.80
P. deltoides	1.77	2.16	3.90
P. I78	6.53	3.13	5.13

Analysis of variance

Source of variation	ss	df	Ms	F
Clones	5155272	5	1011054	41.9 **
Residual	287228	12	23935.7	
Total	5442501	17		

APPENDIX 8

Root shoot ratios of the 3 trees per clone selected as having most typical root systems

Clone	Tree No.	Root weight (air dry) (g)	Shoot weight (air dry) (g)	Root/shoot ratio
S. matsudana	1	54.0	689	.078
	3	35.2	500	.070
	7	48.3	665	.073
S. Booth	3	53.2	305	.174
	5	59.2	545	.109
	7	37.7	242	.156
P. yunnanensis	3	74.6	1094	.068
	5	77.6	1212	.064
	10	57.2	985	.058
P. I488	1	59.4	645	.092
	3	94.8	520	.182
	8	70.9	797	.089
P. deltoides	1	76.8	727	.106
	5	52.8	417	.127
	6	33.8	299	.113
P. I78	3	52.2	328	.159
	4	101.6	496	.205
	7	75.3	519	.145

Analysis of variance

Source of variation	ss	df	Ms	F
Clones	25152	5	5030.4	5.96 **
Residual	10120	12	843.3	
Total	35274	17		

APPENDIX 9

Tensile strength and anatomical characteristics of all test samples of P.I488

sample number	diameter of stele (mm)	specific gravity	percent fibre wall area	fibre length (μ)	fibre width (μ)	percent parenchyma and rays	percent vessel area	vessel diameter (μ)	microfibril angle	tensile strength of stele (kg/mm^2)	fibre wall strength (kg/mm^2)	specific tensile strength (kg/mm^2)
1	2.54	.260	23.6	727	21.3	6.5	37.8	117	36.1	4.96	21.0	19.1
2	2.77	.217	18.0	818	21.1	5.2	47.4	179	38.7	2.38	13.2	11.0
3	3.28	.221	20.7	891	22.7	10.2	45.5	158	36.6	3.10	14.9	14.1
4	3.26	.231	22.4	913	21.9	6.9	46.7	158	39.3	3.45	15.4	15.0
5	2.68	.233	18.4	863	22.6	9.1	49.5	152	34.6	3.23	17.5	13.9
6	2.62	.234	19.8	812	22.0	7.9	45.3	169	36.9	3.17	16.0	13.5
7	2.51	.228	19.4	785	23.2	6.3	45.2	169	35.2	3.52	18.1	15.4
8	3.55	.212	15.1	825	22.3	8.6	47.2	199	37.8	2.83	18.8	13.3
9	3.00	.223	19.5	848	21.7	9.0	43.9	169	37.3	2.92	14.9	13.1
10	3.23	.214	15.7	839	24.0	8.3	45.0	180	37.8	2.70	17.1	12.6
11	3.47	.223	20.8	847	25.2	9.0	43.2	174	36.6	3.05	14.7	13.7
12	3.17	.207	20.8	852	22.0	7.9	43.4	182	37.7	2.97	14.3	14.4
13	4.25	.235	20.8	853	22.3	8.0	41.3	161	37.2	2.84	13.6	12.1
14	3.11	.210	15.2	814	21.6	8.0	47.8	182	36.1	2.57	16.8	12.2
15	2.52	.227	20.8	851	21.3	6.0	47.9	156	38.5	3.11	14.9	13.7
16	3.76	.215	17.2	811	24.6	8.4	46.0	195	35.8	2.59	15.1	12.0
17	2.88	.233	20.5	891	22.4	8.8	43.7	151	35.5	3.96	19.3	17.0
18	2.54	.244	19.4	861	22.7	9.8	43.0	137	34.5	4.17	21.5	17.1
19	3.38	.258	25.6	911	25.9	7.3	36.8	155	35.2	4.91	19.2	19.0
20	3.08	.227	19.7	842	22.7	8.0	44.6	165	36.7	3.28	16.2	14.3

APPENDIX 10

Tensile strength of individual roots of each clone

Sample No.	(mm) diameter	specific gravity	% fibre wall area	tensile strength of stele (kg/mm^2)	fibre wall strength (kg/mm^2)	specific tensile strength (kg/mm^2)
P.178						
1	2.22	.265	25.6	5.22	20.4	19.7
2	2.39	.281	25.0	5.08	20.3	18.1
3	4.09	.243	25.4	4.37	17.2	18.0
4	3.78	.256	24.3	3.74	15.4	14.6
5	2.00	.295	23.1	7.24	31.3	24.5
6	2.00	.322	28.6	7.45	26.1	23.1
7	3.37	.250	25.2	4.86	19.4	19.4
8	3.23	.284	28.3	5.12	18.1	18.0
9	2.70	.266	25.0	3.91	15.6	14.7
10	2.94	.312	27.0	5.15	19.1	16.5
11	2.97	.270	25.9	4.89	18.9	18.1
12	3.44	.244	23.8	3.80	16.0	15.6
13	2.75	.292	29.4	4.45	15.2	15.2
14	3.43	.233	24.8	3.58	14.4	15.4
15	3.23	.251	26.3	4.52	17.2	18.0
16	3.70	.255	25.0	4.55	18.2	17.8
17	4.49	.228	21.3	3.16	14.8	13.9
18	2.80	.260	23.1	4.89	21.2	18.8
19	3.60	.252	25.0	3.12	12.5	12.4
20	3.73	.250	21.6	3.45	14.9	13.8
P.I488						
1	2.54	.260	23.6	4.96	21.0	19.1
2	2.77	.217	18.0	2.38	13.2	11.0
3	3.28	.221	20.7	3.10	14.9	14.1
4	3.26	.231	22.4	3.45	15.4	15.0
5	2.68	.233	18.4	3.23	17.5	13.9
6	2.62	.234	19.8	3.17	16.0	13.5
7	2.51	.228	19.4	3.52	18.1	15.4
8	3.55	.212	15.1	2.83	18.8	13.3
9	3.00	.223	19.5	2.92	14.9	13.1
10	3.23	.214	15.7	2.70	17.1	12.6
11	3.47	.223	20.8	3.05	14.7	13.7
12	3.17	.207	20.8	2.97	14.3	14.3
13	4.25	.235	20.8	2.84	13.6	12.1
14	3.11	.210	15.2	2.57	16.8	12.2
15	2.52	.227	20.8	3.11	14.9	13.7
16	3.76	.215	17.2	2.59	15.1	12.0
17	2.88	.233	20.5	3.96	19.3	17.0
18	2.54	.244	19.4	4.17	21.5	17.1
19	3.38	.258	25.6	4.91	19.2	19.0
20	3.08	.227	19.7	3.28	16.6	14.3

APPENDIX 10 continued

Sample No.	(mm) diameter	specific gravity	% fibre wall area	tensile strength of stele (kg/mm^2)	fibre wall strength (kg/mm^2)	specific tensile strength (kg/mm^2)
P. deltoides						
1	2.35	.267		4.17	18.0	15.6
2	2.52	.255	21.1	3.55	16.9	13.9
3	2.28	.226	19.3	2.74	14.2	12.1
4	2.05	.276	24.8	5.14	20.7	18.6
5	2.80	.239	23.0	4.16	18.2	17.4
6	2.79	.254	20.3	3.33	16.6	13.1
7	1.71	.289	20.0	4.50	22.5	15.6
8	1.97	.274	23.9	4.43	18.5	16.1
9	2.59	.245	18.4	2.84	15.4	11.6
10	2.78	.256	23.6	4.40	18.7	17.2
11	2.11	.284	22.8	5.07	22.3	17.8
12	2.79	.283	23.3	4.17	17.9	14.7
13	3.25	.242	19.9	2.60	13.1	10.7
14	2.20	.268	21.5	4.54	21.1	16.9
15	2.60	.223	18.4	2.59	14.1	11.6
16	3.37	.246	19.6	3.23	16.5	13.1
17	2.90	.245	19.1	3.20	16.7	13.1
18	3.65	.265	24.5	4.71	19.2	17.8
19	3.99	.281	23.5	3.57	15.2	12.7
20	4.21	.263	22.2	2.79	12.6	10.6
P. yunnanensis						
1	3.48	.247	21.8	3.15	16.1	14.2
2	3.81	.241	20.0	2.92	14.6	12.1
3	4.41	.262	27.1	3.90	14.4	14.9
4	4.28	.239	22.1	2.92	13.2	12.2
5	2.61	.252	23.2	4.66	20.1	18.5
6	2.87	.270	23.5	4.92	20.9	18.2
7	2.51	.229	17.6	2.81	16.0	12.3
8	3.02	.226	23.1	3.01	13.0	13.3
9	2.45	.266	22.8	5.24	23.0	19.7
10	2.30	.222	17.0	2.13	12.6	7.6
11	2.90	.213	17.0	2.63	15.4	12.4
12	2.20	.259	21.2	5.04	23.8	19.5
13	3.07	.275	28.5	5.59	19.7	20.3
14	2.78	.243	19.6	3.22	16.4	13.3
15	2.44	.236	21.9	4.15	19.0	17.6
16	3.52	.295	29.4	5.09	17.3	17.3
17	3.15	.214	19.5	3.75	19.2	29.2
18	3.46	.287	34.4	5.37	15.6	18.7
19	3.87	.242	18.7	3.63	19.4	15.0
20	2.56	.224	23.9	3.68	15.6	16.4

APPENDIX 10 continued

Sample No.	(mm) diameter	specific gravity	% fibre wall area	tensile strength of stele (kg/mm^2)	fibre wall strength (kg/mm^2)	specific tensile strength (kg/mm^2)
S. Matsudana						
1	3.29	.265	19.8	3.32	16.8	18.7
2	3.53	.282	23.5	3.05	13.0	10.6
3	2.94	.264	24.8	3.82	15.4	14.4
4	3.43	.281	24.4	4.74	19.4	16.9
5	3.53	.264	23.3	3.39	14.5	12.8
6	4.07	.250	14.8	2.63	17.8	10.5
7	2.30	.185	19.9	3.37	16.9	18.2
8	4.12	.262	22.8	3.21	14.1	12.2
9	3.26	.294	19.5	3.75	19.2	12.7
10	2.86	.230	19.1	2.18	11.5	9.3
11	2.69	.290	21.2	4.10	19.4	14.1
12	2.79	.339	25.8	5.08	19.7	15.0
13	2.53	.332	26.7	3.79	14.2	11.4
14	2.92	.263	21.5	3.76	17.5	14.3
15	2.65	.295	22.2	5.06	22.8	17.1
16	2.90	.293	23.2	4.70	20.3	16.0
17	2.73	.322	23.0	4.33	18.8	13.5
18	3.99	.241	19.9	3.35	16.8	13.9
19	3.91	.134	19.1	2.78	14.5	20.7
20	3.66	.245	19.8	3.06	15.4	12.5
S. Booth						
1	2.69	.215	16.1	2.58	16.0	12.0
2	3.22	.235	17.8	3.12	17.4	13.3
3	4.45	.262	20.3	2.84	14.0	10.8
4	2.67	.255	23.5	3.71	15.8	14.6
5	2.38	.258	21.7	4.66	21.5	18.0
6	2.96	.228	15.6	3.12	20.1	13.7
7	3.13	.267	20.6	4.51	22.0	16.9
8	3.45	.262	24.0	3.91	16.3	13.9
9	3.59	.256	20.0	3.35	16.7	13.1
10	3.28	.240	19.2	3.60	18.8	15.0
11	3.51	.252	20.9	3.72	17.7	14.8
12	2.23	.255	22.7	3.32	14.6	13.0
13	3.17	.226	17.9	3.05	17.0	13.5
14	3.24	.318	26.2	4.73	18.1	14.9
15	2.06	.254	18.7	4.16	22.2	16.4
16	3.23	.241	22.0	3.67	16.7	15.2
17	2.77	.267	18.5	3.99	20.4	15.0
18	3.97	.273	20.3	3.21	15.8	11.8
19	3.75	.275	23.2	3.08	13.3	11.2
20	2.55	.256	22.1	4.45	20.1	17.4

APPENDIX 11

Tensile strength of individual roots collected at monthly intervals throughout the year

Sample No.	(mm) diameter	specific gravity	% fibre wall area	tensile strength of stele (kg/mm^2)	fibre wall strength (kg/mm^2)	specific tensile strength (kg/mm^2)
P. I488 - February						
1	2.02	.239	14.0	3.21	22.9	13.1
2	2.70	.217	13.7	2.93	21.4	13.1
3	2.67	.181	10.4	2.53	24.4	13.5
4	1.88	.215	12.9	3.25	25.2	14.7
5	2.14	.210	13.2	3.96	30.0	18.3
6	2.22	.205	13.3	3.03	22.9	14.8
7	2.82	.206	12.7	3.29	25.9	15.5
8	2.39	.265	15.7	3.96	25.2	14.5
9	3.24	.223	13.5	2.72	20.1	12.2
10	3.01	.211	11.9	2.69	22.6	12.7
March						
1	1.93	.213	12.1	3.52	29.0	15.4
2	2.86	.236	12.9	3.43	26.6	13.5
3	3.17	.184	11.1	2.41	21.7	12.2
4	2.50	.227	12.8	4.38	34.2	18.0
5	3.06	.191	10.6	2.86	27.0	14.1
6	3.24	.202	11.6	2.66	22.9	12.3
7	2.09	.283	15.9	4.55	28.6	15.1
8	1.70	.219	13.5	4.36	32.4	19.9
9	2.43	.223	13.5	3.65	27.1	16.4
10	3.52	.215	12.8	3.18	24.9	14.8
April						
1	1.55	.237	17.8	3.70	20.8	13.5
2	1.92	.275	20.8	4.36	21.0	13.9
3	2.63	.247	14.6	3.25	22.3	11.8
4	2.54	.244	19.8	3.56	18.0	12.6
5	1.82	.248	19.7	4.23	21.5	14.8
6	2.02	.297	18.7	4.55	24.3	13.3
7	2.11	.270	22.6	4.67	20.1	14.1
8	2.25	.252	20.1	4.19	20.8	14.4
9	3.12	.260	20.2	3.48	17.2	13.4
10	3.32	.248	17.6	2.64	15.0	10.6
May						
1	2.00	.293	19.8	5.41	27.3	16.3
2	2.40	.263	21.3	4.19	19.7	14.1
3	1.77	.284	19.6	5.33	27.2	16.5
4	2.75	.262	24.2	4.70	19.4	15.8
5	2.40	.297	23.1	5.03	21.7	15.0
6	2.33	.274	19.8	5.12	25.9	16.5
7	2.83	.324	29.2	7.03	24.0	19.2
8	4.22	.250	22.1	3.51	15.9	12.4
9	3.05	.255	21.0	3.17	15.1	10.9
10	2.86	.252	21.9	4.17	19.1	14.0

APPENDIX 11 continued

Sample No.	(mm) diameter	specific gravity	% fibre wall area	tensile strength of stele (kg/mm^2)	fibre wall strength (kg/mm^2)	specific tensile strength (kg/mm^2)
June	- see results of between clone tests.					
July						
1	2.40	.278	20.2	4.57	22.6	18.5
2	2.62	.265	22.6	3.65	16.2	15.5
3	2.26	.280	19.9	4.28	21.5	17.2
4	2.49	.281	25.9	4.50	17.4	18.1
5	2.16	.255	23.9	4.21	17.6	18.6
6	3.34	.244	18.3	2.59	14.1	12.0
7	3.52	.280	24.3	4.60	18.9	18.5
8	3.56	.258	21.6	3.81	17.6	16.7
9	2.56	.266	22.8	5.13	22.5	21.8
10	2.37	.250	19.3	3.87	20.0	17.4
August						
1	2.64	.269	20.4	4.04	19.8	16.0
2	2.48	.291	21.3	5.01	23.5	18.4
3	3.15	.252	18.3	3.85	21.0	16.4
4	2.46	.273	23.3	4.45	19.1	17.4
5	3.09	.257	24.9	4.85	19.5	20.1
6	2.12	.267	16.8	4.25	25.3	17.0
7	2.28	.256	18.1	3.87	21.4	16.1
8	2.46	.244	18.8	4.25	22.6	18.6
9	2.78	.265	23.9	4.38	18.3	17.6
10	2.15	.278	18.1	4.31	23.8	16.6
September						
1	2.73	.226	18.4	5.03	27.5	22.3
2	3.06	.226	17.8	5.49	30.8	29.3
3	2.83	.236	18.5	4.12	22.2	17.5
4	2.37	.229	17.9	4.40	24.6	19.2
5	2.87	.209	16.1	3.77	23.5	18.0
6	2.44	.214	15.5	5.06	32.7	23.6
7	3.20	.217	22.6	2.82	22.9	13.0
8	3.09	.225	23.9	5.80	24.2	25.8
9	2.61	.245	17.3	5.36	31.0	21.9
10	3.46	.226	19.3	4.94	25.6	21.9
October						
1	3.26	.205	18.3	4.48	24.5	21.9
2	3.44	.250	21.2	4.77	22.5	19.1
3	3.71	.205	19.6	4.71	24.1	23.0
4	2.14	.213	16.2	4.39	27.1	20.6
5	2.20	.240	25.4	5.84	23.0	24.3
6	1.74	.221	19.1	4.69	24.6	21.2
7	2.49	.212	19.2	4.07	21.2	19.2
8	2.49	.190	18.8	4.83	25.7	25.4
9	2.68	.206	16.4	4.00	24.4	19.4
10	2.71	.205	17.0	3.96	23.3	19.3

APPENDIX 11 continued

Sample No.	(mm) diameter	specific gravity	% fibre wall area	tensile strength of stele (kg/mm^2)	fibre wall strength (kg/mm^2)	specific tensile strength (kg/mm^2)
November						
1	2.94	.190	17.3	3.84	23.0	20.2
2	2.07	.163	14.4	3.20	24.6	19.6
3	2.63	.173	14.2	3.31	23.2	19.1
4	2.95	.176	15.2	3.69	24.0	21.0
5	3.32	.216	21.2	4.73	24.0	21.9
6	3.36	.182	18.0	3.52	16.4	19.3
7	3.00	.254	21.6	4.91	19.9	19.3
8	4.62	.169	14.7	2.86	16.0	16.9
9	4.08	.156	14.3	2.63	19.3	16.8
10	3.43	.201	18.1	4.01	27.6	20.0
December						
1	3.00	.186	19.5	3.34	20.2	18.0
2	3.85	.159	16.0	2.42	16.4	15.2
3	2.07	.257	22.4	4.65	19.9	18.1
4	1.96	.197	19.6	4.38	23.6	22.2
5	2.84	.147	13.7	3.10	18.0	21.1
6	3.01	.189	18.0	2.85	16.3	15.1
7	3.08	.158	13.2	2.25	16.7	14.2
8	2.59	.162	14.3	3.21	23.0	19.8
9	2.91	.227	17.9	3.50	18.6	15.4
10	4.29	.163	14.4	2.30	17.2	14.1
January						
1	2.33	.222	18.9	3.67	19.0	16.5
2	2.36	.177	20.3	3.06	19.6	17.3
3	2.64	.157	16.2	2.57	17.3	16.4
4	4.36	.186	18.2	2.98	16.4	16.0
5	2.16	.208	19.1	3.57	20.4	17.2
6	2.02	.239	22.1	4.15	21.6	17.4
7	4.33	.189	17.7	3.10	15.7	16.4
8	3.42	.160	14.2	2.83	18.1	17.7
9	4.30	.176	13.3	2.61	14.3	14.8
10	3.26	.207	16.0	3.68	17.6	17.8

APPENDIX 11 continued

Sample No.	(mm) diameter	specific gravity	% fibre wall area	tensile strength of stele (kg/mm^2)	fibre wall strength (kg/mm^2)	specific tensile strength (kg/mm^2)
S. matsudana						
February						
1	3.87	.233	14.1	2.30	16.3	9.6
2	2.85	.236	15.3	2.57	16.8	10.5
3	2.00	.222	13.0	2.98	23.0	13.1
4	3.94	.221	13.6	2.38	17.5	10.5
5	3.00	.219	14.7	2.23	15.2	9.9
6	2.89	.199	12.2	1.76	14.4	8.6
7	2.98	.220	13.5	2.47	18.3	10.9
8	2.34	.234	15.2	3.00	19.7	12.5
9	2.90	.220	12.9	2.82	21.8	12.8
10	3.31	.226	15.1	2.80	18.5	12.4
March						
1	2.86	.260	15.0	3.58	23.8	13.3
2	2.43	.205	12.2	3.42	28.0	16.0
3	2.45	.272	14.1	4.14	29.4	14.6
4	4.18	.250	13.9	2.70	19.5	10.4
5	2.57	.218	12.4	3.76	30.3	16.5
6	2.36	.241	13.4	3.43	25.6	13.7
7	2.90	.244	14.3	3.02	21.1	12.4
8	3.17	.248	13.5	3.24	24.0	13.1
9	3.33	.238	13.6	2.84	20.9	11.9
10	3.43	.234	13.5	2.60	19.2	11.1
April						
1	1.97	.336	24.6	5.08	20.7	12.5
2	1.88	.277	16.8	4.42	26.3	13.2
3	1.88	.300	19.6	4.80	24.5	13.2
4	1.87	.296	19.1	4.31	22.6	12.0
5	1.99	.259	15.1	4.53	30.0	14.4
6	2.57	.321	19.0	4.42	23.3	11.4
7	3.49	.257	15.6	3.50	22.4	11.2
8	3.11	.246	16.0	3.31	20.7	11.2
9	2.58	.354	23.2	4.77	20.5	11.2
10	3.53	.294	18.5	3.19	17.2	10.9
May						
1	1.90	.320	14.6	4.56	31.3	11.6
2	2.16	.270	14.7	3.42	23.2	10.1
3	2.45	.273	15.2	3.58	23.6	10.5
4	3.94	.334	19.1	4.00	20.9	9.6
5	1.92	.381	27.6	6.08	22.0	13.0
6	2.88	.338	16.1	3.98	24.7	9.5
7	2.46	.342	19.1	5.03	26.4	12.0
8	2.11	.428	25.8	7.31	28.3	14.1
9	2.95	.378	28.5	4.31	15.1	9.3
10	2.66	.351	22.4	4.50	20.2	10.4

APPENDIX 11 continued

Sample No.	(mm) diameter	specific gravity	% fibre wall area	tensile strength of stele (kg/mm^2)	fibre wall strength (kg/mm^2)	specific tensile strength (kg/mm^2)
June	- see results of between clone tests					
July						
1	3.01	.272	21.7	3.86	17.8	14.2
2	3.25	.241	16.1	3.17	19.7	13.1
3	2.77	.239	18.7	3.09	16.6	12.9
4	3.25	.280	22.5	4.36	19.3	15.6
5	3.34	.235	16.4	3.09	18.8	13.1
6	3.81	.262	19.5	3.87	19.8	14.5
7	2.94	.256	19.6	3.71	18.9	14.5
8	2.59	.294	22.7	4.29	18.9	14.6
9	2.76	.250	20.5	2.98	14.5	11.9
10	3.36	.293	21.9	4.65	21.2	15.9
August						
1	2.93	.246	17.6	3.07	17.5	12.5
2	2.35	.263	23.1	4.27	18.5	16.2
3	2.66	.250	18.0	3.78	21.0	15.1
4	3.05	.289	22.5	4.44	19.7	15.4
5	3.15	.246	22.3	3.79	17.0	15.4
6	3.27	.275	21.1	3.80	18.0	13.8
7	2.62	.277	21.4	4.48	20.9	16.1
8	2.98	.252	21.0	4.23	20.1	16.8
9	2.77	.243	18.8	3.36	17.9	13.9
10	4.49	.290	23.3	3.99	17.1	13.8
September						
1	3.51	.223	16.9	4.51	26.7	20.2
2	3.06	.249	25.9	5.43	20.9	21.8
3	3.27	.320	28.2	7.84	27.8	24.5
4	2.83	.234	21.3	4.18	19.6	17.9
5	2.99	.269	21.9	4.88	22.2	18.1
6	2.24	.236	23.1	5.19	22.5	22.0
7	2.45	.246	19.4	4.28	22.0	17.4
8	2.34	.254	20.1	5.98	29.7	23.5
9	4.02	.231	18.7	4.01	21.5	17.6
10	3.63	.217	20.6	3.95	19.2	18.2
October						
1	2.82	.258	21.2	5.94	28.0	23.0
2	2.39	.214	22.9	5.53	24.2	25.8
3	4.43	.236	21.0	4.25	20.2	18.0
4	3.40	.224	18.9	4.58	24.3	20.4
5	3.36	.213	16.2	3.28	22.4	15.4
6	3.35	.268	25.2	5.26	20.9	19.6
7	3.52	.227	19.2	4.11	21.4	18.1
8	2.97	.220	16.2	3.55	21.9	16.1
9	2.89	.192	14.7	3.95	26.9	20.6
10	4.33	.261	21.5	4.75	22.8	18.2

APPENDIX 11 continued

Sample No.	(mm) diameter	specific gravity	% fibre wall area	tensile strength of stele (kg/mm^2)	fibre wall strength (kg/mm^2)	specific tensile strength (kg/mm^2)
November						
1	3.23	.188	16.4	3.32	17.0	17.7
2	3.04	.279	24.2	4.89	16.7	17.5
3	1.92	.218	17.9	4.01	20.5	18.4
4	2.01	.236	19.7	4.85	21.6	20.6
5	2.60	.226	18.7	4.21	18.1	18.6
6	2.69	.266	23.8	4.50	17.4	16.9
7	2.41	.211	17.9	3.83	20.4	18.2
8	4.65	.251	18.3	4.31	14.7	17.2
9	2.02	.347	25.1	6.24	23.5	18.0
10	2.83	.252	20.6	4.54	19.1	18.0
December						
1	3.65	.267	25.2	4.42	21.0	16.6
2	3.98	.256	20.6	3.75	16.5	14.6
3	4.59	.177	18.3	2.05	15.2	11.6
4	2.42	.198	18.3	3.14	18.2	15.9
5	3.08	.219	17.4	3.53	19.5	16.1
6	2.06	.184	19.6	3.42	24.0	18.6
7	2.56	.164	19.5	3.61	23.9	22.0
8	3.43	.291	26.5	4.95	21.0	17.0
9	2.60	.197	17.5	3.00	19.8	15.2
10	2.03	.204	20.1	4.23	20.9	20.7
January						
1	4.01	.186	20.9	2.30	16.9	12.4
2	2.66	.197	18.4	2.64	18.3	13.4
3	4.44	.193	18.3	2.32	15.1	12.0
4	2.14	.218	20.8	3.60	22.4	16.5
5	3.00	.152	14.6	2.51	21.0	16.5
6	3.10	.213	17.4	2.97	19.2	13.9
7	2.68	.187	16.9	2.42	17.2	12.9
8	2.30	.237	20.4	4.01	21.4	16.9
9	3.30	.214	21.6	3.52	20.5	16.4
10	1.97	.200	21.0	3.51	20.0	17.6

APPENDIX 12

STRESS/STRAIN RELATIONSHIPS

The following data were obtained from the stress/strain diagrams, and were used for the comparison of the stress/strain relationships of the six clones.

Clone	Sample No.	Diameter of stele (mm)	Ultimate strain (%)	Ultimate stress (kg/mm^2)	Ultimate stress/ Ultimate strain	Young's modulus
P. I78	1	2.16	15.9	7.19	.452	1.97
	2	2.80	17.8	6.00	.337	2.10
	3	3.05	17.2	4.96	.290	1.44
	4	3.35	17.6	3.98	.226	1.18
P. I488	1	2.67	16.0	4.30	.268	1.10
	2	2.77	16.6	3.68	.222	0.85
	3	3.33	18.5	2.88	.156	0.88
	4	4.00	16.0	3.06	.191	0.76
P. deltoides	1	2.18	13.8	3.43	.249	1.07
	2	2.39	10.9	3.08	.283	1.18
	3	2.95	13.3	2.12	.159	0.62
	4	3.11	11.4	2.15	.189	0.80
P. yunnanensis	1	2.36	18.2	4.15	.228	1.10
	2	2.59	25.2	3.68	.146	1.24
	3	2.88	17.3	4.34	.250	1.27
	4	3.05	14.0	3.92	.289	1.32
S. Matsudana	1	3.00	18.2	4.10	.225	1.18
	2	3.22	17.5	3.05	.174	0.86
	3	3.25	15.5	5.03	.324	1.29
	4	3.32	16.6	4.85	.292	1.08
S. Booth	1	2.45	18.5	4.85	.262	1.76
	2	2.87	16.6	3.50	.214	1.26
	3	3.28	17.5	4.54	.260	1.59
	4	3.73	16.5	4.24	.257	1.81

APPENDIX 13

Calculation of predicted loads required to remove the root systems of the three selected trees per clone.

Clone	Tree No.	Total cross sectional area of steles at breaks (mm^2)	Mean diameter of steles at breaks (mm)	Typical tensile strength of root of this diameter* (kg/mm^2)	Predicted load required (kg)
P. I78	3	76.8	2.0	6.1	468
	4	78.1	2.0	6.1	476
	7	119.6	2.5	5.5	655
P. I488	1	103.3	2.3	3.69	381
	3	96.7	2.4	3.63	351
	8	146.5	2.7	3.48	510
P. yunnanensis	3	62.6	1.5	4.14	259
	5	56.9	1.6	4.13	235
	10	55.6	1.5	4.14	230
P. deltoides	1	74.1	2.3	4.03	299
	5	50.0	1.6	4.40	220
	6	53.5	2.1	4.13	221
S. matsudana	1	89.1	2.3	4.32	384
	3	46.1	1.7	4.74	219
	7	72.3	2.1	4.46	322
S. Booth	3	47.2	1.9	4.15	196
	5	61.4	1.8	4.19	257
	7	39.6	1.9	4.15	164

* From regression of tensile strength of the stele on diameter of the test sample (Appendix 18)

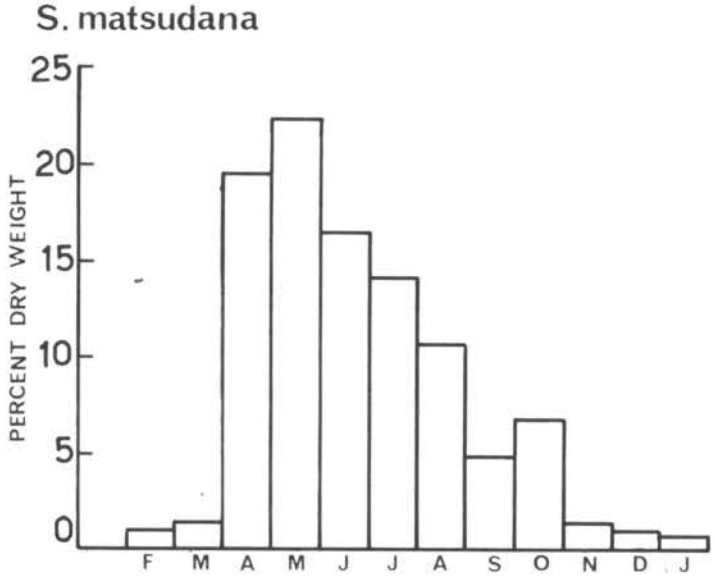
APPENDIX 14

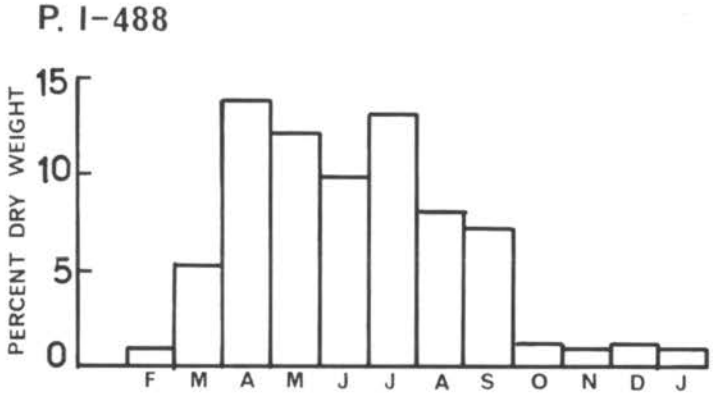
Calculation of estimated overall tensile strength of a 5mm. diameter root, including cortex, for each clone

Clone	% of cross-section area of root that is stele	cross-sectional area of stele of root of diameter 5mm.	diameter of stele (calculated)	typical tensile strength of the stele, for given diameter	calculated load required to break root	estimated overall tensile strength of a 5mm. diameter root (kg/mm^2)
P. I78	27.5	5.40	2.62	5.69	30.73	1.57
P. I488	30.7	6.03	2.77	3.44	20.74	1.06
P. deltoides	25.1	4.94	2.51	3.87	19.12	0.98
P. yunnanensis	46.1	9.05	3.33	4.33	39.18	2.00
S. matsudana	50.3	9.87	3.43	3.43	33.85	1.72
S. Booth	47.1	9.25	3.52	3.52	32.56	1.66

* From regression of tensile strength on the diameter of the stele.

Appendix 15. Seasonal variation in the starch content of roots of P. I-488 and S. matsudana





APPENDIX 16

MISCELLANEOUS ANALYSES OF VARIANCE

Source of variation	SS	df	MS	F
A. Proportion of fibrous roots in the root systems				
Total	287.06	17		
Clones	273.44	5	54.68	54.89 **
Blocks	3.66	2	1.80	1.80 NS
Residual	9.96	10	.996	
B. Porportion of the cross-sectional area of the roots that was stele				
Total	1263731	93		
Clones	1069600	5	213920	99.6 **
Blocks	39582	16	2473	1.15 NS
Residual	154548	72	2146	
C. Effect of rate of extension on tensile strength of roots				
Total	5.39	19		
Rate of Extension	.052	1	.0521	2.63 NS
Blocks	3.55	9	.394	19.89 **
Residual	1.79	9	.0198	
D. Inter-clonal variation in ultimate strain				
Total	178.53	23		
Clones	92.87	5	18.57	4.38 **
Blocks	13.59	3	4.53	1.07 NS
Residual	72.06	17	4.24	
E. Inter-clonal variation in ultimate stress/ultimate strain				
Total	104982	23		
Clones	35324	5	7064	1.99 NS
Blocks	9213	3	3071	.86 NS
Residual	60445	17	3555	
F. Inter-clonal variation in Young's modulus				
Total	3.379	23		
Clones	2.243	5	.4486	7.76 **
Blocks	.153	3	.0508	.878 NS
Residual	.983	17	.0578	

APPENDIX 17

Correlation coefficients between tensile strength and anatomical characteristics in roots of P. I488

	strength of stele	fibre wall strength	specific tensile strength	specific gravity	diameter of stele	% fibre wall area	fibre length	fibre width	microfibril angle	% rays and parenchyma	% vessel area	vessel diameter
tensile strength of stele	1	.75**	.98**	.90**	-.34NS	.74**	.04NS	.20NS	-.10NS	-.05NS	-.73**	-.79**
fibre wall strength		1	.77**	.58**	-.40NS	.11NS	-.16NS	.13NS	-.62NS	-.16NS	-.37NS	-.51*
specific tensile strength			1	.80**	-.35NS	.70NS	.08NS	.20NS	-.48*	.00NS	-.68**	-.74**
specific gravity				1	-.26NS	.75**	.00NS	.14NS	-.43*	-.13NS	-.69**	-.85**
diameter of stele					1	-.08NS	.29NS	.41NS	.20NS	.28NS	-.16NS	.47*
% fibre wall area						1	.27NS	.16NS	-.06NS	-.21NS	-.70**	-.67**
fibre length							1	.27NS	.11NS	.37NS	.23NS	-.01NS
fibre width								1	-.41NS	.29NS	-.36NS	.19NS
microfibril angle									1	-.42NS	.28NS	.35NS
% rays and parenchyma										1	.02NS	.03NS
% vessel area											1	.48*
vessel diameter												1

APPENDIX 18

Regression analyses of tensile strength on the diameter of the test sample for each clone.

	r	signi-ficance	b	sd	a
1. Tensile strength of the stele					
P. I78	-.783	**	-1.322	.247	8.784
P. I488	-.336	NS	- .514	.376	4.868
P. deltoides	-.429	*	- .539	.267	5.266
P. yunnanensis	-.092	NS	- .147	.376	4.362
S. matsudana	-.489	*	- .712	.299	5.955
S. Booth	-.400	NS	- .420	.226	4.949
2. Fibre wall strength					
P. I78	-.717	**	-4.555	1.040	32.63
P. I488	-.403	NS	-2.056	1.101	22.98
P. deltoides	-.613	*	-2.619	.796	24.61
P. yunnanensis	-.411	NS	-2.040	.532	23.56
S. matsudana	-.315	NS	-1.617	1.147	22.08
S. Booth	-.541	*	-2.379	.871	25.14
3. Specific tensile strength					
P. I78	-.672	**	-2.992	.777	26.68
P. I488	-.352	NS	-1.682	1.053	19.50
P. deltoides	-.488	*	-1.729	.812	19.26
P. yunnanensis	-.052	NS	- .245	1.556	16.05
S. matsudana	-.141	NS	- .761	1.258	16.68
S. Booth	-.617	**	-2.063	.620	20.65

Abbreviations

r	=	correlation coefficient
b	=	regression coefficient
s.d.	=	standard deviation of the regression coefficient
a	=	constant in the regression equation
NS	=	not significant
*	=	significant at 5% level
**	=	significant at 1% level

APPENDIX 19

Regression analyses of tensile strength on the diameter of the test sample, for each group of monthly samples.

	r	signi-ficance	b	sd	a
1. Tensile strenth of the stele					
(a) P. I488					
February	-.550	NS	-.6044	.324	4.673
March	-.774	*	-.9437	.273	6.001
April	-.737	*	-.8344	.270	5.805
May	-.490	NS	-.7944	.499	6.880
June	-.336	NS	-.5139	.340	4.868
July	-.361	NS	-.4792	.429	5.403
August	-.077	NS	-.0817	.373	4.116
September	-.102	NS	-.2694	.926	5.451
October	-.092	NS	-.0967	.371	4.843
November	-.303	NS	-.3114	.347	4.679
December	-.858	*	-.9931	.209	6.139
January	-.562	NS	-.3094	.161	4.187
(b) S. matsudana					
February	-.467	NS	-.3005	.202	3.435
March	-.792	*	-.6772	.184	5.283
April	-.846	*	-.8290	.185	6.245
May	-.413	NS	-.8055	.628	6.725
June	-.489	*	-.7119	.299	5.955
July	-.187	NS	-.3099	.576	2.743
August	-.055	NS	-.0434	.278	4.052
September	-.221	NS	-.4479	.699	6.384
October	-.248	NS	-.3327	.459	5.633
November	-.294	NS	-.2851	.327	5.251
December	-.184	NS	-.1747	.329	4.141
January	-.662	*	-.5243	.209	4.532
2. Fibre wall strength					
(a) P. I488					
February	-.505	NS	-3.115	1.881	31.88
March	-.731	*	-4.613	1.522	39.67
April	-.733	*	-3.454	1.134	28.14
May	-.790	*	-5.179	1.418	35.31
June	-.403	NS	-2.055	1.102	22.97
July	-.450	NS	-2.360	1.654	25.28
August	-.647	*	-4.183	1.741	32.14
September	-.365	NS	-4.001	3.614	37.97
October	-.225	NS	- .715	1.094	26.03
November	-.582	*	-3.049	1.505	31.68
December	-.656	*	-2.433	.989	26.10
January	-.902	*	-2.119	.357	24.61

Abbreviations : As in Appendix 18

APPENDIX 19 continued

	r	significance	b	sd	a
Fibre wall strength					
(b) S. matsudana					
February	-.524	NS	-2.406	1.382	25.39
March	-.800	*	-5.905	1.463	42.13
April	-.614	*	-3.208	1.459	30.80
May	-.533	NS	-3.925	2.203	33.55
June	-.315	NS	- .863	1.148	20.15
July	-.616	*	-3.167	1.433	8.71
August	-.504	NS	-1.326	.802	22.78
September	-.203	NS	-1.237	2.112	26.96
October	-.581	*	-2.314	1.144	31.04
November	-.865	*	-2.825	.579	26.64
December	-.695	*	-2.309	.897	27.02
January	-.730	*	-2.112	.698	25.45
3. Specific tensile strength					
(a) P. I488					
February	-.506	NS	-2.002	1.205	19.26
March	-.720	*	-2.848	.970	22.72
April	-.710	*	-1.580	.554	16.92
May	-.524	NS	-1.820	1.044	19.91
June	-.152	NS	- .790	1.054	17.08
July	-.386	NS	-1.817	1.595	22.38
August	-.069	NS	- .173	1.207	17.55
September	-.079	NS	- .873	3.921	23.25
October	-.105	NS	- .456	1.526	22.61
November	-.587	NS	-1.307	.636	23.64
December	-.715	*	-2.978	1.029	26.14
January	-.565	NS	- .548	.283	18.46
(b) S. matsudana					
February	-.507	NS	-1.302	.783	14.99
March	-.846	*	-2.929	.652	21.99
April	-.771	*	-1.327	.387	15.42
May	-.659	*	-1.734	.699	15.42
June	-.141	NS	- .761	1.258	16.68
July	.387	NS	1.358	1.143	9.84
August	-.401	NS	- .932	.752	17.72
September	-.301	NS	-1.358	1.523	24.24
October	-.566	NS	-2.756	.930	28.74
November	-.560	NS	- .710	.371	20.05
December	-.799	*	-2.596	.834	24.72
January	-.710	*	-1.895	.664	20.46

APPENDIX 20

Regression analysis of seasonal variation in tensile strength on chemical composition of roots.

	r	signi-ficance	a	sd	b
A. Tensile strength of the stele					
P. I488					
cellulose	-.158	NS	-.0686	.135	6.933
lignin	.306	NS	.1378	.135	.8082
hemicelluloses	-.311	NS	-.0849	.0819	5.166
lignin/cellulose ratio	.356	NS	6.421	5.331	.6601
S. matsudana					
cellulose	-.684	*	-.2319	.078	13.65
lignin	-.094	NS	-.0461	.154	4.778
hemicelluloses	.211	NS	-.0703	.103	2.628
lignin/cellulose ratio	.370	NS	7.672	6.093	.2544
B. Fibre wall strength					
P. I488					
cellulose	.375	NS	.8828	.689	-17.61
lignin	.612	*	1.494	.610	
hemicelluloses	.058	NS	.0856	.466	20.34
lignin/cellulose ratio	.382	NS	37.28	28.56	2.932
S. matsudana					
cellulose	-.042	NS	-.0460	.064	22.57
lignin	.102	NS	.1634	.503	17.39
hemicelluloses	-.252	NS	.2740	.332	25.45
lignin/cellulose ratio	.149	NS	10.11	21.13	15.88
C. Specific tensile strength					
P. I488					
cellulose	.491	NS	-.9840	.551	60.54
lignin	.687	*	1.428	.477	-15.05
hemicelluloses	-.694	*	-.8728	.286	30.00
lignin/cellulose ratio	.858	**	71.38	13.49	-19.01
S. matsudana					
cellulose	-.461	NS	-.6440	.392	42.36
lignin	.541	*	1.094	.538	-6.52
hemicelluloses	-.303	NS	-.4163	.414	22.50
lignin/cellulose ratio	.865	**	73.93	13.54	19.59

Abbreviations : As in Appendix 18

APPENDIX 21

Regression analysis of seasonal variation in the tensile strength of the stele on the actual amounts of chemical components present per unit volume of root.

	f	Significance	b	sd	a
P. I488					
Cellulose	.393	NS	17.23	3.36	2.15
Hemicellulose	-.063	NS	5.08	23.56	4.11
Lignin	.671	*	71.24	22.29	0.32
Specific Gravity	.474	NS	8.70	5.82	1.89
S. matsudana					
Cellulose	.205	NS	10.29	15.04	2.78
Hemicellulose	.355	NS	24.33	18.71	2.78
Lignin	.533	NS	81.24	41.38	-0.13
Specific Gravity	.516	NS	10.57	5.96	1.20

Abbreviations : As in Appendix 18

Covariance analyses of inter-clonal variation in tensile strength, with diameter of the stele as the concomitant variable. (Method of Snedecor & Cochran, 1967)

A. Tensile strength of the stele

	df	x^2	xy	y^2	Red^n	Deviations from Regression df	SS	MS
Clones	5	2.62	1.34	21.17				
Error	114	42.03	-11.58	188.98	3.19	133	185.8	1.64
C+E	119	44.65	-10.24	210.15	2.35	118	207.8	
						5	22.01	4.402*

B. Fibre wall strength

	df	x^2	xy	y^2	Red^n	Deviations from Regression df	SS	MS
Clones	5	2.62	.033	37.85				
Error	114	42.03	-112.65	1100.75	301.9	113	799.8	7.078
C+E	119	44.65	-112.62	1138.6	284.1	118	954.5	
						5	54.7	10.94 NS

C. Specific tensile strength

	df	x^2	xy	y^2	Red^n	Deviations from Regression df	SS	MS
Clones	5	2.62	4.07	243.6				
Error	114	42.03	-75.26	836.6	134.8	113	701.8	6.21
C+E	119	44.65	-71.19	980.2	113.5	118	866.7	
					3	5	164.9	33.0**

Adjusted means

	tensile strength of stele (kg/mm^2)	fibre wall strength (kg/mm^2)	specific tensile strength (kg/mm^2)
P. I78	4.65	18.6	18.5
P. I488	3.29	16.7	14.3
P. yunnanensis	3.91	17.4	15.7
P. deltoides	3.70	16.6	13.9
S. matsudana	3.71	17.3	14.5
S. Booth	3.66	17.9	14.3
LSD (5%)	0.81	1.68	1.57
LSD (1%)	1.07	2.28	2.08

APPENDIX 23

Covariance analyses of seasonal variation in tensile strength with diameter of the stele as the concomitant variable.

P. I488

A. Tensile strength of the stele

	df	x^2	xy	y^2	Red^n	Deviations from Regression df	SS	MS
Months	11	8.44	-4.90	39.79				
Error	108	40.32	-21.85	57.31	11.84	107	45.47	.425
M+E	119	48.76	-26.75	47.10	14.68	118	82.42	
						11	36.95	3.359**

B. Fibre wall strength

	df	x^2	xy	y^2	Red^n	Deviations from Regression df	SS	MS
Months	11	8.44	-33.77	1223.4				
Error	108	40.31	-117.13	1018.0	340.3	107	677.7	6.33
M+E	119	48.75	-150.90	2241.4	467.1	118	1774.3	
						11	1096.6	99.7**

C. Specific tensile strength

	df	x^2	xy	y^2	Red^n	Deviations from Regression df	SS	MS
Months	11	8.44	34.04	738.3				
Error	108	40.32	-60.04	563.6	91.20	107	472.4	4.41
M+E	119	48.76	-26.60	1301.9	14.51	118	1287.4	
						11	815.0	74.09**

Adjusted means

	tensile strength of stele (kg/mm^2)	fibre wall strength (kg/mm^2)	specific tensile strength (kg/mm^2)
February	3.01	23.3	13.8
March	3.42	27.0	15.0
April	3.61	18.8	12.5
May	4.70	21.1	14.9
June	3.60	17.9	15.1
July	4.14	18.6	17.3
August	4.20	20.7	17.1
September	4.72	26.7	20.9
October	4.57	24.0	21.3
November	3.91	23.1	18.7
December	3.29	19.4	17.6
January	3.40	19.0	17.3
LSD (5%)	0.58	2.25	1.88
LSD (1%)	0.77	2.98	2.49

APPENDIX 24

Covariance analyses of seasonal variation in tensile strength, with diameter of the stele as the concomitant variable.

S. matsudana

A. Tensile strength of the stele

	df	x^2	xy	y^2	Red^n	Deviations from Regression df	SS	MS
Months	11	6.29	-4.16	64.57				
Error	108	45.16	-11.57	102.31	2.96	107	99.35	.929
M+E	119	51.45	-15.73		4.81	118	162.07	
						11	62.72	5.701**

B. Fibre wall strength

	df	x^2	xy	y^2	Red^n	Deviations from Regression df	SS	MS
Months	11	6.29	-13.14	723.0				
Error	108	45.16	-112.46	1307.3	1307.3	107	1027.3	9.60
M+E	119	51.45	-125.60	2030.3	306.6	118	1723.6	
						11	696.3	63.30

C. Specific tensile strength

	df	x^2	xy	y^2	Red^n	Deviations from Regression df	SS	MS
Months	11	6.29	42.84	1029.9				
Error	108	45.16	-67.81	512.8	101.84	107	410.95	3.84
M+E	119	51.45	-24.97	1542.7	12.12	118	1530.58	
						11	1119.63	101.78**

Adjusted means

	tensile strength of stele (kg/mm^2)	fibre wall strength (kg/mm^2)	specific tensile strength (kg/mm^2)
February	2.51	18.4	11.2
March	3.28	24.3	13.3
April	4.11	21.7	11.4
May	4.58	22.6	11.6
June	3.78	17.1	15.1
July	3.75	19.0	14.4
August	3.94	19.0	15.0
September	5.05	23.4	20.2
October	4.62	24.3	20.1
November	4.42	18.4	18.4
December	3.66	20.2	17.1
January	2.66	19.2	14.4
LSD (5%)	0.86	2.76	1.54
LSD (1%)	1.14	3.66	2.04

APPENDIX 25

Multiple regression analyses of tensile strength of the stele (y) on specific gravity (X1), diameter of the stele (X_2), percent vessel area (X_3), vessel diameter (X_4), and percent rays and parenchyma (X_5)

1. Regression coefficients

N.B. b = true regression coefficients
B = standardised partial regression coefficients

a. Regression of Y on X1, X2, X3, X4, X5

b1	=	2.4249	B1	=	.4881
b2	=	-.2796	B2	=	-.1826
b3	=	-1.0255	B3	=	-.4485
b4	=	-.2216	B4	=	-.0592
b5	=	.4963	B5	=	.0890

b. Regression of Y on X1, X2, X3, X4 only

b1	=	2.0361	B1	=	.4098
b2	=	-.3840	B2	=	-.2507
b3	=	-1.0312	B3	=	-.4510
b4	=	-.4302	B4	=	-.1150

c. Regression of Y on X1, X2, X3 only

b1	=	2.5285	B1	=	.5089
b2	=	.4428	B2	=	.2761
b3	=	1.0034	B3	=	.4388

d. Regression of Y on X1, X2 only

b1	=	4.3087	B1	=	.8672
b2	=	-.1615	B2	=	-.1055

Analysis of variance of multiple regression

Source of variation	SS	df	MS	F	
Total	96968.6	18	5387.14		
Regression on X1, X2, X3, X4, X5	85179.6	15	17035.9	18.8	**
Regression on X1, X2, X3, X4	85542.1	4			
Regression on X5 after X1, X2, X3, X4	362.5	1	362.5	.399	NS
Deviations	11789.1	13	906.85		
Regression on X1, X2, X3, X4	85542.1	4	21385.5	26.2	**
Regression on X1, X2, X3	85260	3			
Regression on X4 after X1, X2, X3	282.1	1	282.1	.345	NS
Deviations	11426.5	14	816.2		
Regression on X1, X2, X3	85260	3	28420	36.4	**
Regression on X1, X2	78713.4	2			
Regression on X3 after X1, X2	6546.6	1	6546.6	8.39	**
Deviations	11708.6	15	780.6		
Regression on X1, X2	78713.4	2	39356.7	34.5	**
Regression X1	77710.5	1			
Regression on X2 after X1	1002.9	1	1002.9	.879	
Deviations	18255.6	16	1140.9		

Variance of Y attributable to X1, X2, X3, X4, X5 = 83.2%
" X1, X2, X3, X4 = 84.5%
" X1, X2, X3 = 85.5%
" X1, X2 = 78.8%
" X1 = 79.0%

APPENDIX 26

Multiple regression analysis of tensile strength of fibre walls (Y) on microfibril angle (X_1), diameter of stele (X_2), fibre width (X_3), and fibre length (X_4).

1. Regression coefficients

a. Regression of Y on X1, X2, X3, and X4.

b1	=	-.8783	B1	=	-.4917
b2	=	-.1661	B2	=	-.3254
b3	=	.1527	B3	=	.0842
b4	=	-.0329	B4	=	-.0600

b. Regression of Y on X1, X2 and X3 only

b1	=	-.8949	B1	=	-.5010
b2	=	-.1705	B2	=	.3340
b3	=	.1226	B3	=	.0675

c. Regression of Y on X1 and X2 only

b1	=	-.9547	B1	=	-.5345
b2	=	-.1530	B2	=	-.2997

d. Regression of Y on X1 only

b1	=	-1.0578	B1	=	-.5922

Analysis of variance of multiple regression

Source of variation	SS	df	MS	F	
Total	10774.7	18	598.6		
Regression on X1, X2, X3, X4	4773.6	4	1193.4	2.78	NS
Regression on X1, X2, X3	4739.6	3			
Regression on X4 after X1, X2, X3	34.0	1	34.0	.079	NS
Deviations	6001.2	14	428.7		
Regression on X1, X2, X3	4739.6	3	1579.9	3.93	
Regression on X1, X2	4710.1	2			
Regression on X3 after X1, X2	29.5	1	29.5	.073	NS
Deviations	6035.2	15	402.3		
Regression on X1, X2	4710.1	2	2355.1	6.21	**
Regression on X1	3778.2	1			
Regression on X2 after X1	931.9	1	931.9	2.46	NS
Deviations	6064.6	16	379.0		
Regression on X1	3778.2	1	3778.2	9.18	**
Deviations	6996.6	17	411.6		
Regression on X1, X2, X3, X4	4773.6	4			
Regression on X1	3778.2	1			
Regression on X2, X3, X4 after X1	995.4	1	995.4	2.32	NS
Deviations	6001.2	14	428.7		

Variations in Y attributable to X1, X2, X3, X4 = 28.4%
" X1, X2, X3 = 32.8%
" X1, X2 = 36.7%
" X1 = 31.3%

APPENDIX 27

Multiple regression analysis of specific tensile strength (Y), on microfibril angle (X_1), diameter of stele (X_2), fibre width (X_3), and fibre length (X_4).

1. Regression coefficients

a. Regression of Y on X1, X2, X3, and X4

b1	=	-.8944	B1	=	-.3504
b2	=	-.2957	B2	=	-.4053
b3	=	.4637	B3	=	.1789
b4	=	.1307	B4	=	.1666

b. Regression of Y on X1, X2 and X3 only

b1	=	-.8284	B1	=	-.3245
b2	=	-.2783	B2	=	-.3814
b3	=	.5833	B3	=	.2251

c. Regression of Y on X1 and X2 only

b1	=	-1.1126	B1	=	-.4358
b2	=	-.1952	B2	=	-.2675

d. Regression of Y on X1 only

b1	=	-1.2441	B1	+	-.4874

Analysis of variance of multiple regression

Source of variation	SS	df	MS	F	
Total	22004.8	18	1222.6		
Regression on X1, X2, X3, X4	7938.8	4	1984.7	1.98	NS
Regression on X1, X2, X3	7407.5	4			
Regression X4 after X1, X2, X3	531.3	1	531.3	.528	NS
Deviations	14067.0	14	1004.8		
Regression on X1, X2, X3	7404.5	3	2469.2	2.54	NS
Regression on X1, X2	6743.2	2			
Regression on X3 after X1, X2	664.3	1	664.3	.683	NS
Deviations	14598.3	15	973.2		
Regression on X1, X2	6743.2	2	3371.6	3.54	NS
Regression on X1	5226.5	1			
Regression on X2 after X1	1516.7	1	1516.7	1.59	NS
Deviations	15262.6	16	953.9		
Regression on X1	5226.5	1	5226.5	5.29	*
Deviations	16779.3	17	987.0		
Regression on X1, X2, X3, X4	7938.8	4			
Regression on X1	5226.5	1			
Regression on X2, X3, X4 after X1	2712.2	3	904.1	1.11	NS
Deviations	14067.0	14	1004.8		

Variation in Y attributable to	X1, X2, X3, X4	=	17.8%
"	X1, X2, X3	=	20.4%
"	X1, X2	=	21.3%
"	X1	=	19.3%

APPENDIX 28

Multiple regression analysis of soil binding capacity (as the root system strength index) (Y) on the estimated overall tensile strength of individual roots (X_1) and the proportion of fibrous roots in the root system (as percent of total air-dry weight) (X_2)

1. Regression coefficients

b1	=	.674	B1	=	.130
b2	=	.381	B2	=	.808

2. Analysis of variance

Source of variation	df	SS	MS	F	
Total	5	21.65	4.33		
Regression on X1 + X2	2	17.92	8.96	7.23	NS
Regression on X1 alone	1	11.71	11.71	9.44	NS
Regression on X2 alone	1	17.76	17.76	14.32	*
Regression on X2 after X1	1	6.21	6.21	5.01	NS
Regression on X1 after X2	1	0.16	0.16	0.13	NS
Deviations	3	3.73	1.24		