Forschungszentrum Karlsruhe
Technik und Umwelt

Wissenschaftliche Berichte
FZKA 5518

The Shape of Tree Root Systems Affects Root Wood Strength

A. Stokes
Institut für Materialforschung

Januar 1995

Forschungszentrum Karlsruhe
Technik und Umwelt
Wissenschaftliche Berichte
FZKA 5518

The Shape of Tree Root Systems Affects Root Wood Strength

A. Stokes

Institut für Materialforschung

Forschungszentrum Karlsruhe GmbH, Karlsruhe

1995

Forschungszentrum Karlsruhe GmbH
Postfach 3640, 76021 Karlsruhe

ISSN 0947-8620

The Shape of Tree Root Systems Affects Root Wood Strength

Abstract

Mature tree root systems can be categorised into three groups on the basis of their woody root architecture: heart, tap and plate systems. The lateral roots are important for transferring external loading forces into the ground, which helps maintain tree stability. In order to determine if the distribution of lateral root strength is related to the shape of the system and the forces withstood, wood samples were taken from roots of various mature tree species and the strength tested.

Root strength decreased along the root at different rates, depending on the type of root system present. Lateral roots in plate root systems were relatively stronger further away from the stem than laterals in heart and tap root systems. Wood strength in some species with plate systems was found to increase along the lateral roots, before decreasing again. It appears that the increase in strength coincides with the point of maximum bending of the root as the tree sways in the wind. Strength was also found to increase on the underside of lateral roots in the plate systems of poplar. The underside of these roots will experience high compression stresses due to the weight of the tree pushing the root onto the hard, bearing surface of the soil.

External loading forces in plate root systems will be transmitted into the soil further away from the stem due to the lack of branches, therefore a high strength along the root will help resist mechanical stress. The high rate of branching near the stem, or large rigid main tap root, found in heart and tap root systems, respectively, allows a faster dissipation of forces nearer the stem, therefore a high investment in strength further along the root is not necessary.

Die Art des Wurzelsystems eines Baumes bedingt die Festigkeit des Wurzelholzes

Zusammenfassung

Wurzelsysteme älterer Bäume kann man aufgrund ihrer holzigen Wurzelarchitektur in drei Kategorien einteilen: stark verzweigte tiefe Herzwurzler, Pfahlwurzler und Flachwurzler. Für eine Übertragung von äußeren Belastungen (z.B.: Wind) in den Boden sind seitliche Wurzeln von Bedeutung, die dem Baum seine Stabilität geben. Um zu entscheiden, ob die Verteilung der Festigkeiten in den lateralen Wurzeln in Beziehung steht zur Art des Wurzelsystems und den Kräften, die diese übertragen muß, wurden Holzproben aus Wurzelholz von älteren Bäumen mit dem Zuwachsbohrer entnommen und deren Festigkeiten getestet.

Die Festigkeiten des Holzes nahmen entlang der Wurzeln in unterschiedlichem Maße ab. Diese Abnahme war abhängig von der jeweiligen Art des Wurzelsystems. Laterale Wurzeln von flachwurzelnden Bäumen waren fester als Wurzeln von Herz- und Pfahlwurzlern. Bei einigen Arten von Flachwurzlern erhöhte sich die Festigkeit des Wurzelholzes entlang der lateralen Wurzeln bis zu einen Maximum, um dann wieder abzunehmen. Dieses Festigkeitsmaximum scheint mit dem Punkt zusammen zu fallen, wo maximale Biegespannungen in den Wurzeln auftreten, wenn der Baum vom Wind bewegt wird. Außerdem erhöhten sich die Festigkeiten auf der unteren Seite der Wurzeln bei flachwurzelnden Pappeln. Die Unterseite dieser Wurzeln erfährt hohe Druckspannungen, da das Gewicht des Baumes die Wurzeln auf die harte tragende Erde drückt.

Äußere Belastungen werden bei Flachwurzlern mit weniger verzweigten Wurzeln in der Nähe des Stammes stammfern in den Boden übertragen. Deshalb helfen höhere Festigkeiten entlang der seitlichen Wurzeln, den mechanischen Belastungen zu widerstehen. Eine hohe Verzweigung von Wurzeln nahe am Stamm (Herzwurzel) oder große feste Pfahlwurzeln erlauben eine bessere Verteilung der Belastung stammnah in die Erde. Deshalb brauchen Bäume mit solchen Wurzeln auch keine erhöhten Festigkeiten entlang der seitlichen Wurzeln.

CONTENTS

1.1 INTRODUCTION

The stability of a tree depends on its overall shape and strength and particularly important is the type of root system present. External loading forces *e.g.* wind must be transferred down the stem to the roots and then into the ground in order to prevent mechanical failure of the tree. If the root system is inadequate for anchorage, then the tree will "topple" (bend or break at the root or stem base) (Burdett 1979) or uproot due to wind forces. Therefore, tree root systems must be large enough to transfer forces into the ground and strong enough in highly stressed areas to prevent breakage.

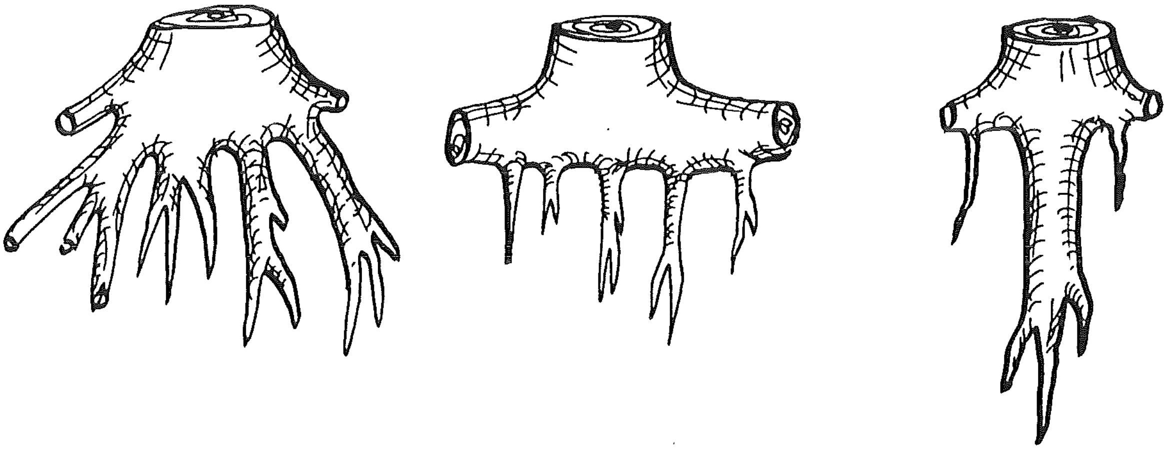
Little attention has been paid to the mechanics of the tree anchorage system until recently (Coutts 1983, 1986, Mattheck 1993, Ennos 1993, 1994, Stokes 1994, Stokes *et al.* 1995b, Teschner & Mattheck 1994). Ennos (1994) attributes this lack of research to the intuitive knowledge that the uprooting of a plant will indeed be resisted by the friction between the roots and the soil. Also, as roots are underground, they are easier to ignore and more difficult to study, although new non-invasive techniques are being developed *e.g.* nuclear magnetic resonance imaging of non-woody roots (Southon *et al.* 1992) and radar imaging of tree roots in the field (A.H. Fitter, pers. comm.). However, as theoretical and practical studies on biomechanics increase, researchers are finding that there exist many different ways in which plants are anchored, and that the mechanics of the root system might be manipulated in order to increase stability.

1.2 Root Form

The forces a plant must withstand will probably determine the shape of root system it develops (Ennos & Fitter 1992). When the crowns of trees are subjected to wind, the tree stems act as long lever arms producing high bending moments which must be counterbalanced by the root-soil moment in order to prevent trees from falling. Woody plants must therefore have a rigid element in the root system in order to resist the rotational moments transmitted by the stem (Ennos 1993). There are distinct ways in which this is achieved in different tree species due to the type of root system present. Tree root systems were originally categorized into three groups by Büsgen (1929), depending on their basic three-dimensional form. The most common type of root system found in angiosperms is a "heart" system, where horizontal and vertical laterals develop from the base of the tree (Fig. 1.1a). "Plate" systems are often found in gymnosperms *e.g.* spruce and consist of horizontal lateral roots spreading out from the base of the tree stem (Fig. 1.1b). Vertical sinker roots develop and grow downwards from the main lateral roots. A third type of root system found in fewer tree species is one where a large tap root anchors the tree directly, like a stake in the ground (Fig. 1.1c) and horizontal lateral roots act like guy ropes (Ennos 1993). However, the shape of a root system is largely determined by site conditions. For example, a deep rooting species *e.g.* larch (*Larix* sp.) develops a very shallow root system if grown on soils where seasonally high water tables develop. The vertical roots often die due to waterlogging and a valuable component of the anchorage system is lost.

Fig. 1.1.

The three basic types of tree root form
(after Köstler *et al.* 1968)



a) Heart b) Plate c) Tap root

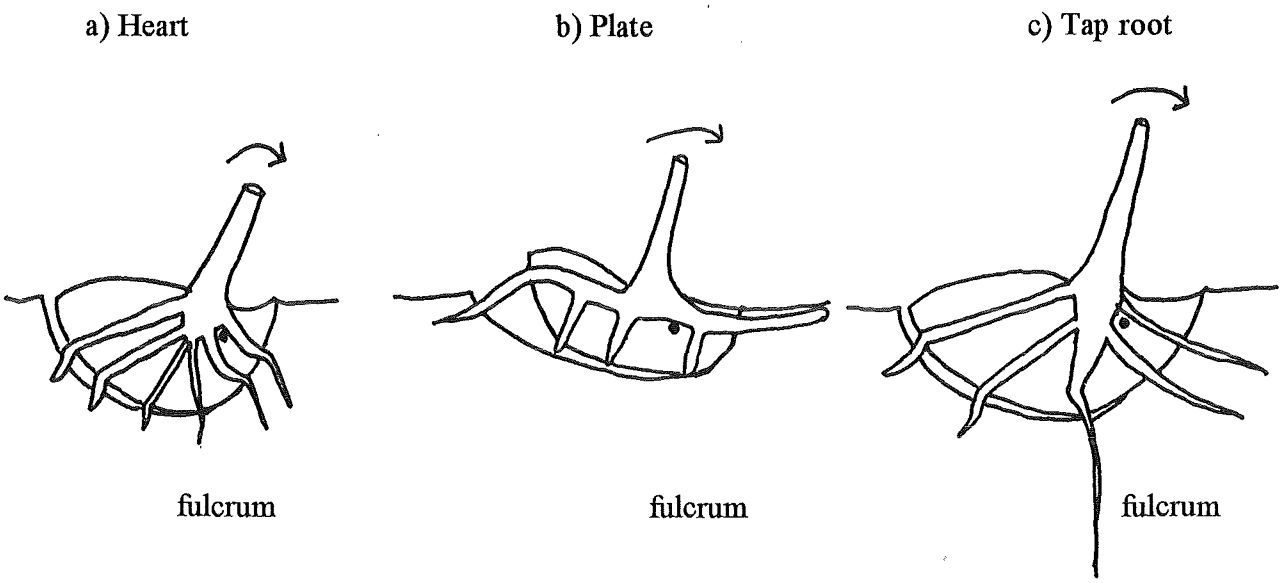
1.3 The Mechanics of Anchorage

Two types of root system (heart and plate) resist uprooting initially by the weight of the root and soil mass. However, the most important component in resisting uprooting is that of the "windward" roots which are pulled upwards during overturning. Tensile and shearing forces are then present in the windward part of the root-system and must be transferred to the soil. A further but less important contribution to tree stability is provided by the bending resistance of the leeward roots during uprooting. If a root is considered to be a circular cantilever beam, then its stiffness is related to the second moment of area (a function of radius to the fourth power). If the root branches into two forks of an even size with a total cross-sectional area equivalent to the parent, the total stiffness of the beam will be halved. Therefore, branching on the leeward side of tree root systems will cause a reduction in stiffness. The point at which the root-soil plate is levered out of the ground (the fulcrum) would then occur closer to the stem and stability would be reduced (Coutts 1983, 1986) (Fig. 1.2). The position of the fulcrum is particularly important in shallow rooting plate systems, where branching is often minimal and vertical roots may not always be present, depending on local conditions.

In heart and tap root systems, the position of the leeward fulcrum, or hinge, is closer to the tree stem because of the greater number of vertical roots anchoring the tree centrally. Therefore, the length, diameter and branching pattern of the horizontal lateral roots on the leeward side is less important.

Fig. 1.2

Position of the leeward fulcrum in different types of root systems
(after Coutts 1983, 1986, Ennos *et al.* 1993)


a) Heart b) Plate c) Tap root

The transfer of tension from the roots to the soil is a fundamental part of root anchorage. If we consider the roots in the soil as elastic fibres of a high tensile strength embedded in a matrix of plastic soil, when a root is pulled out of that matrix, tractive forces between the two develop. The tractive forces are produced by bonding between the root and surrounding soil matrix and they mobilize the tensile resistance in the root. If the adhesion between the root and soil is less than the strength of the soil matrix, the root will pull out, linked only by weak frictional forces as in clay soil (Waldron 1977, Gray 1978, Waldron & Dakessian 1981). If the root-soil bond is greater than the strength of the soil matrix, the root will be pulled out still linked to the soil *via* the remaining shear resistance of the soil. If the soil matrix tensile strength is less than its shear strength, failure of the soil in tension may occur, as is the case with roots growing in very wet soils. Most windthrow occurs during winter storms when the soil is so wet that the shear resistance tends to be an order of magnitude greater than the soil tensile strength (Coutts 1983).

The type of branching pattern found in root systems may determine their ability to resist uprooting. As roots are less stiff than the surrounding soil matrix (Coutts 1983, Ennos 1994), tension applied to the top of the root will cause the root to stretch at its upper part and shear past the soil as it is pulled upwards. Tension will gradually be transferred to the soil. The greater the applied force, the greater the area of soil around the root will fail and the the greater the length of the root that will be stretched. The tensile strength of a root is influenced by its diameter (Wu 1976, Ennos 1990) and for a number of roots can be determined per unit area of soil by calculating the distribution of root sizes in a specific cross-section (Wu 1976). However, the tensile strength of roots must be fully mobilized during failure *i.e.* the roots must be long enough and / or frictional enough so that the frictional bond between the roots and the soil matrix exceeds the tensile strength of the roots. Too short a root will slip, or pull out before mobilizing the maximum tensile resistance and breaking in tension. Therefore, an increase in root branching per unit volume of soil may increase anchorage (Ennos 1990, Stokes *et al.* 1995c) because tension will be transferred more rapidly into the soil.

1.4 Optimization of the Root System

Tree stability will be enhanced if resources for structural growth are utilised in an optimum manner. If new or denser wood is laid down faster areas of high mechanical stress, the rigidity of that area increases, thereby reducing the initial stress. Such growth, with secondary thickening in mechanically vulnerable regions, will result in a tree with an even distribution of stress over its surface. This "Axiom of Uniform Stress," as termed by Mattheck (1993) would explain the cause of localised woody growth in trees, such as the swelling around root bases and wounds (Mattheck 1991). For example, in wind exposed trees, resources are redistributed so that root bases often develop eccentrically with extra growth forming on the upper and lower sides of the root. The resulting shape is similar to an I-beam (Mattheck & Breloer 1992, Stokes 1994), or if there is extra growth on the upper or lower side only, a T-bar shaped root will be produced (Jacobs 1954, Fayle 1968, 1976, Wilson 1975). A root shaped in such a way should be able to resist imposed bending stresses more efficiently than a root with a more even distribution of secondary thickening around its circumference.

Features which have been identified as contributing to anchorage further away from the root bases, include an increase in the number and size of branches per unit volume of soil in the windward lateral roots of wind stressed *Picea sitchensis* (Stokes *et al.* 1995b). Windward and leeward lateral roots of wind stressed *P. sitchensis* and *Larix decidua* were also found to increase in number and size (Stokes *et al.* 1995a). As a tree sways in the wind, windward and leeward lateral roots are placed under the most stress, therefore more and larger roots in these directions would help counteract wind loading on the tree. Such changes in root system morphology under an imposed loading force show that cambial activity must be influenced by external environmental factors. Internal root structure may therefore also be affected by loading forces such as wind or soil slippage on hillsides. A change in wood anatomy *e.g.* cell wall thickness or density would alter mechanical properties but has been investigated more in stems (see Telewski 1995) than in roots (Hathaway & Penny 1975). If root strength can be increased by changes at the cellular level due to external loading, it is important to identify exactly how these changes are instigated, so that they may be manipulated to increase stability.

1.5 Basic Anatomy

Angiosperm (broad-leaved dicotyledenous species) and gymnosperm (coniferous species with needle shaped leaves) trees possess different types of wood which inherently affects wood strength (see *e.g.* Kramer & Kozlowski 1979, for a more detailed description). Secondary vascular tissue (xylem) forms during ageing, the principal function of which is the upward translocation of water and solutes. Secondary xylem also provides the mechanical support in trees. In gymnosperms, the xylem consists of water conducting axially oriented tracheids, parenchyma cells and epithelial cells. Transverse cells present include ray tracheids, ray parenchyma and ray epithelial cells, used for radial water transport and resource storage. Angiosperms are distinct from coniferous species in that they contain water conducting vessel elements in the xylem as well as fibres and parenchmya. Ray tracheids are not present. Hardwoods can be classified further into two groups: ring porous and diffuse porous (see Schweingruber 1990). Ring porous trees have large water conducting vessels formed mainly in the spring and early summer and with narrower elements formed later in the year. Diffuse porous trees show little or no seasonal variation in vessel size, therefore growth rings are difficult to discern. The water conducting vessels may decrease wood strength locally, as they usually have thinner walls than other cells. Failure which initiates cracking of the xylem will occur preferentially in the locality of the larger vessel cells, as fracture across the cell walls *i.e. intracellularly,* costs less energy than fracture through the middle lamella and primary wall *i.e. intercellularly* (Boatwright & Garrett 1983).

Compared to that of the stem, the anatomy of the root varies considerably (see Fayle 1968). Pith is absent; the parenchyma content is usually higher and fibre content lower than that of stem; in hardwoods, the number of vessels per unit area is often less; heartwood is infrequent; the annual rings are less well defined and contain fewer cells than the corresponding stem ring. Rootwood cells are wider, longer and less lignified with thinner cell walls and larger pits. Therefore, it can be expected that rootwood is weaker than stemwood, especially in hardwoods (Riedl 1937), although whether this applies to *all* roots in an entire system, and to what extent is unknown. The pattern of cell structure in woody roots is known to differ according to the position of the root in the root system. Cells at the root base and in the sinker roots are usually as, or denser with thicker cell walls than in the stem (Fayle 1968), which correspond to those parts of the root system under the most stress as the tree sways in the wind. Therefore, strength has probably also increased in these regions, but has only been investigated in the buttress roots of forest trees (Albrecht & Mattheck 1994), where it was found to increase in the areas of highest stress.

Responses of tree root systems to external stresses has received little attention until recently (Nicoll *et al.* 1995, Stokes *et al.* 1995a,c) as due to the increasing number of storms, losses of timber and urban trees due to windthrow has increased dramatically (Grayson 1989, Mattheck & Breloer

1994). The identification of characteristics contributing to tree stability is therefore important for future breeding programs and for helping foresters and arboriculturists decide which species to plant in a particular site. In this investigation, the strength of roots from different forest trees was quantified in order to determine whether external loading affected wood quality. Two values for wood strength were measured: the maximum stress required to break the wood and also to cause plastic deformation. The strength was correlated to root system form and the transfer of wind forces into the ground. Wood samples were taken from the roots of mature tree species with different types of root systems and wood anatomy. The trees sampled were located at two sites in south west Germany; a frequently flooded, flat area next to the Rhine and strongly sloping, dry ground in the Palatinian forest. The wood strength was tested along the length of lateral and some sinker roots. The strength of lateral roots growing downhill was compared to that of those uphill. Differences in wood strength were then discussed with relation to root anatomy and the forces to which root systems are subjected.

2.1 MATERIALS AND METHODS

2.1.1 Choice of trees

Mature trees with different types of root systems were examined in order to determine differences in strength distribution along the lateral roots. The trees examined were a mixture of gymnosperms and angiosperms (both ring and diffuse porous) so that differences between wood and root system type could be examined (Table 2.1).

Table 2.1

Types of trees examined

Type of root system	**Type of wood**		
	Gymnosperm	**Angiosperm**	
		ring porous	**diffuse porous**
PLATE	Norway spruce *(Picea abies)*	Common ash *(Fraxinus excelsior)*	poplar *(Populus nigra & P. italiensis)*
HEART	European larch *(Larix decidua)*	Sweet chestnut *(Castanea sativa)*	beech *(Fagus sylvatica)*
TAP	Scots pine *(Pinus sylvestris)*	none found	

(Köstler *et al.* 1968, Schweingruber 1990).

The trees examined were located in two sites: a frequently, flooded, flat area next to the Rhine river (Fig. 2.1, ash and poplar sp.) and strongly sloping, dry ground in the Palatinian forest, S.W. Germany (Figs. 2.2, 2.3, beech, Sweet chestnut, larch, Scots pine and Norway spruce). A random selection of trees over 40 years old were made with a breast height diameter (DBH) of 35 +/- 10 cm.

Fig. 2.1

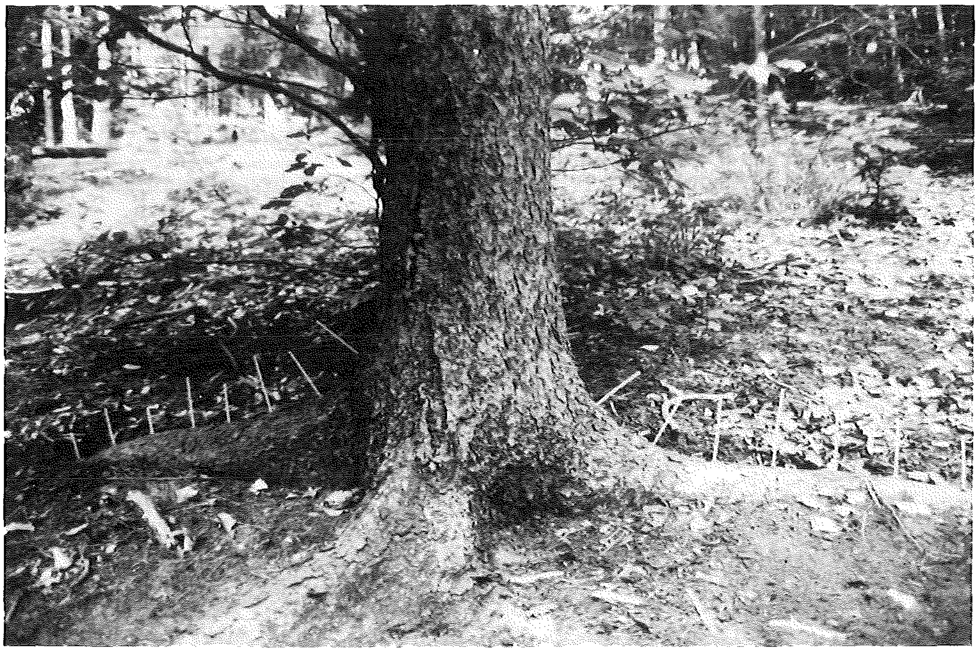
Ash growing on frequently flooded flat ground next to the Rhine river

Fig. 2.2

Beech growing on strongly sloped ground in the Palatinian forest

Fig. 2.3

Norway spruce growing on sloped ground in the Palatinian forest



2.1.2 Sampling

In order to determine how strength is distributed within the first order lateral roots (1°L's) of trees with different types of root systems, wood samples were removed from the 1°L's and the strength of the wood tested. Cores (5 mm diameter) were extracted with a borer perpendicular to the fibre direction, at regular intervals along the length of the root, starting from the buttress (Fig. 2.4). Ten 1°L's per tree species were examined. The number of cores taken per root varied, depending on its length, but at least five cores per root were taken. Two cores were also taken from the stem at breast height so that relative wood strength could be compared between species. Points where the roots branched were noted and the cross-sectional area (CSA) of the root was measured at each drilling point. Wood cores were taken through the entire height of a root where possible.

The extracted wood cores were then broken at 12 mm intervals along their length, using a Fractometer (Mattheck *et al.* 1994). The Fractometer measures the lateral bending strength (in the radial direction of the wood) and the compression strength parallel to the direction of fibre alignment (Fig. 2.5).

Fig. 2.4

Wood samples were removed from the lateral roots and stem at DBH

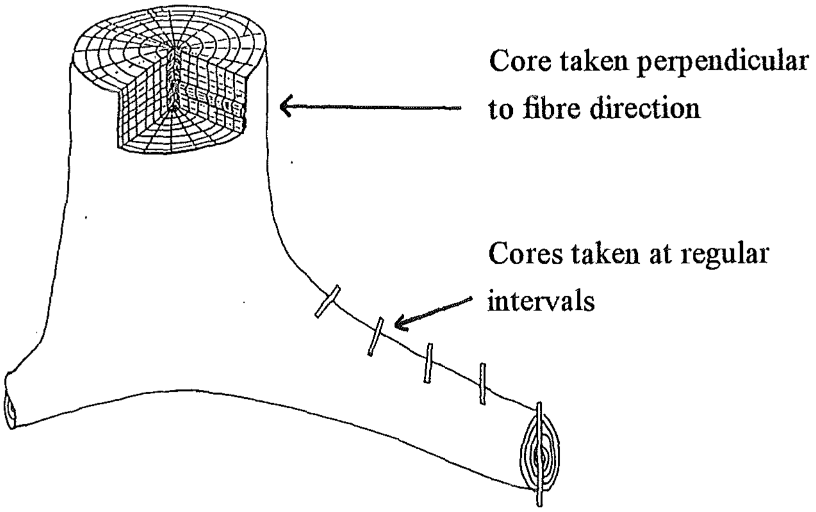
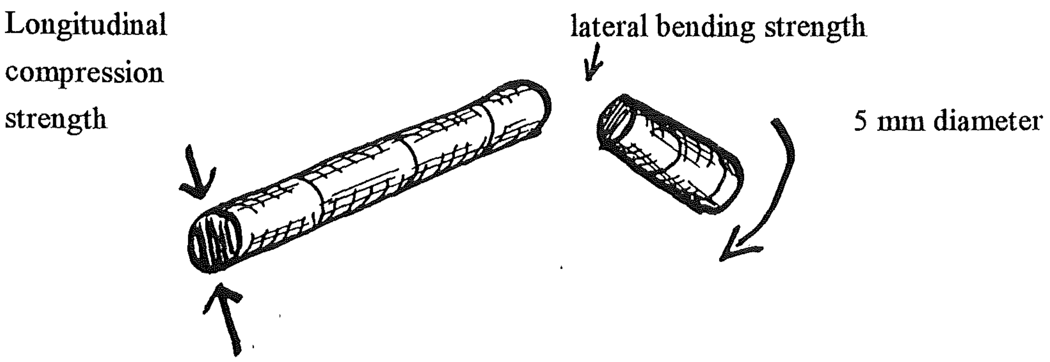


Fig. 2.5

The increment core was broken and two types of wood strength was measured



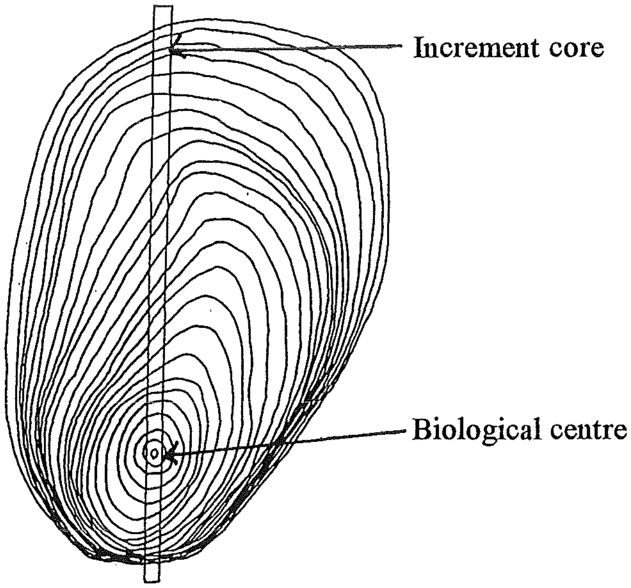
3.1 RESULTS

3.1.1 Analysis of results

The values obtained for lateral bending strength depend heavily on the angle at which the increment core was taken. As lateral roots grow, they twist and turn, usually in one direction only *e.g.* clockwise (Wilson 1964), therefore the biological centre of the root is often displaced to one side (Fig. 3.1). If a core is taken from the middle of the root, it will not necessarily be positioned through the biological centre, therefore will not always be aligned perpendicular to the growth rings.

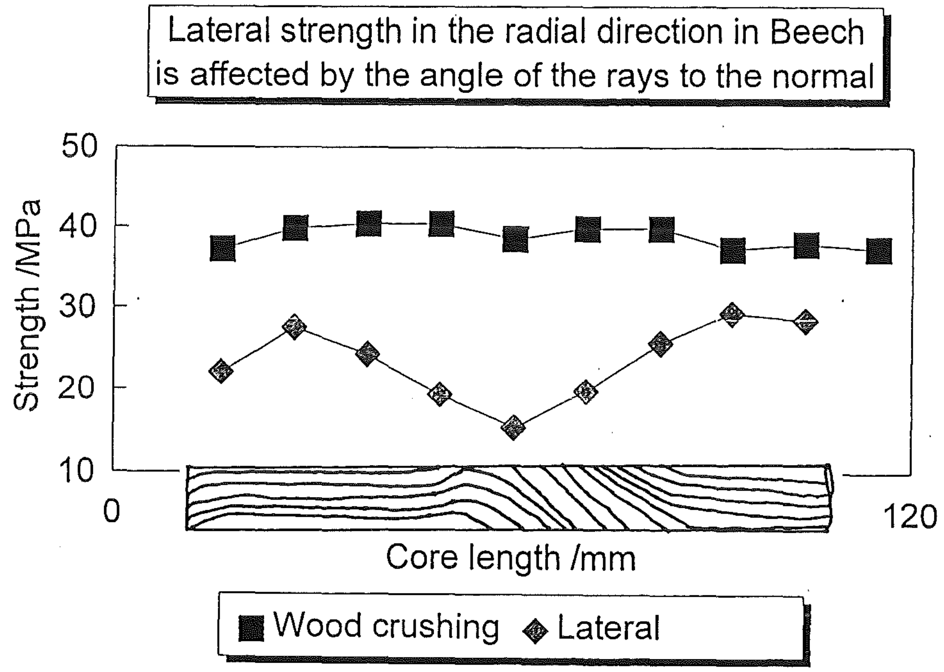
Fig. 3.1

Example of a cross-section through an eccentric root, showing the position of a badly aligned increment core



When the core is broken (in order to obtain lateral bending strength values), it fractures parallel to the growth ring. If the growth ring is not perpendicular to the core, neither will be the fracture. As the lateral bending strength is related to the number and size of the wood rays (Mattheck *et al.* 1994), the angle of the rays is therefore also important. If the angle in the radial direction is not parallel to the growth rings, lateral bending strength values are lower (Fig. 3.2). However, compression strength values appear to be unaffected (Fig. 3.2). If the core is taken perfectly aligned to the fibre direction, and through the centre of the root, the values may still not be reliable, depending on the history of the root *e.g.* when branching occurs, the fibres around the branching point are displaced. If the branch dies, it is not externally obvious that this region may yield unreliable values. Therefore cores must be examined as they are extracted. If the growth rings or rays are not parallel to the core direction, the strength values will influence the mean and should therefore be excluded. In angiosperms, rays are usually multiserate (many cells wide) and therefore have a large influence on lateral bending strength, whereas rays in gymnosperms are uniserate (single cell wide) and have less inflence on strength. Therefore, lateral bending strength distribution throughout 1°L's of has largely been ignored, whereas compression strength has been examined in all the tree species. In the analysis of lateral bending strength along the root, only the surface values were used in the angiosperms, because the outer growth rings are usually parallel to the surface and so the values are reliable.

Fig. 3.2



The mean lateral bending and compression strength was calculated for each increment core taken (except in angiosperms when only the lateral bending strength surface value was taken). The core samples were classified in distance classes of 10 cm from the stem, *i.e.* 0 - 4 cm, 5 - 14 cm, 15 - 24 cm *etc.* because it was not always possible to take samples at specified distances from the stem due to the presence of *e.g.* a branching point. The mean values were then calculated for each distance class for the ten roots of each tree species.

3.2 Root shape

Both poplar species and Norway spruce had long lateral roots with little taper and few branches, whereas ash, also possessing a plate system, had much shorter lateral roots, which tapered rapidly but were also not very branched. The poplars and ashes were growing on seasonally waterlogged ground and so were susceptible to winter dieback of the roots and fungal attack due to the wet conditions. The vertical sinker roots of the trees examined were either dead or underdeveloped with many thin, weak "shaving-brush" type roots present (Fraser & Gardiner 1968). All the ash trees examined were decayed in the centre of the trunk at the base of the tree, therefore the area around the hollow was highly buttressed in order to provide support for the tree (Mattheck &

Breloer 1993). The wood in the region of high buttressing was much stronger than anywhere else in the tree (Fig. 3.3). This zone of strong wood probably biases the root strength results in that they will be very high at the root-stem joint, therefore unusually high values from this region were removed from the analysis. The poplars were not found to be decayed in the trunk centre, although a wet, brown rot was sometimes found in the centre of the lateral roots, which decreased root strength in that region (Fig. 3.4).

Fig. 3.3

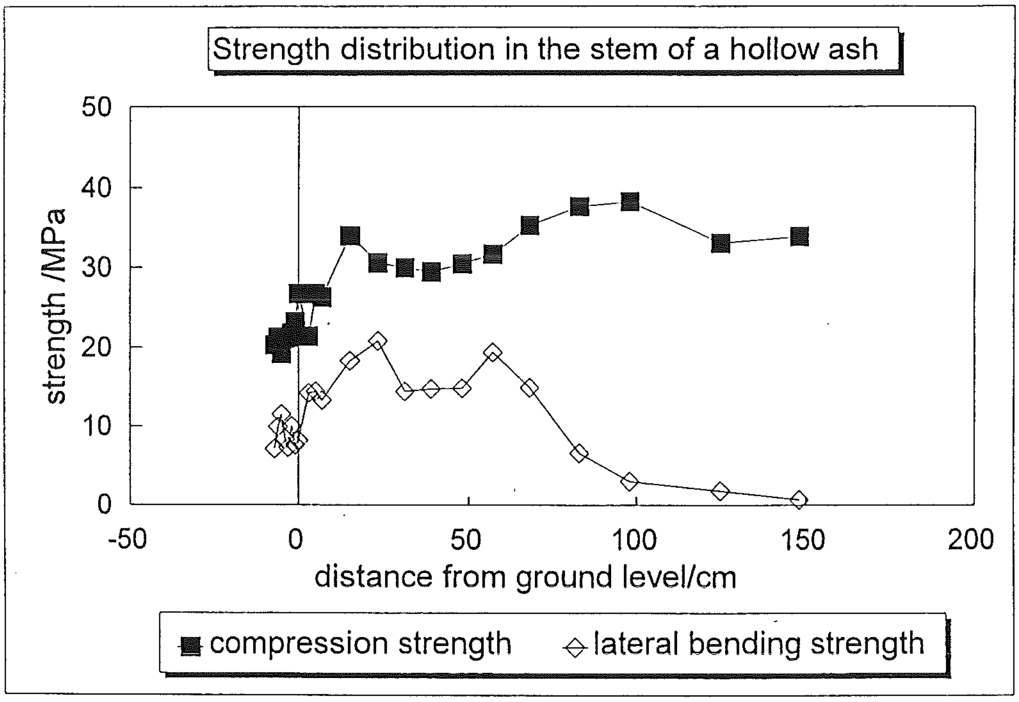
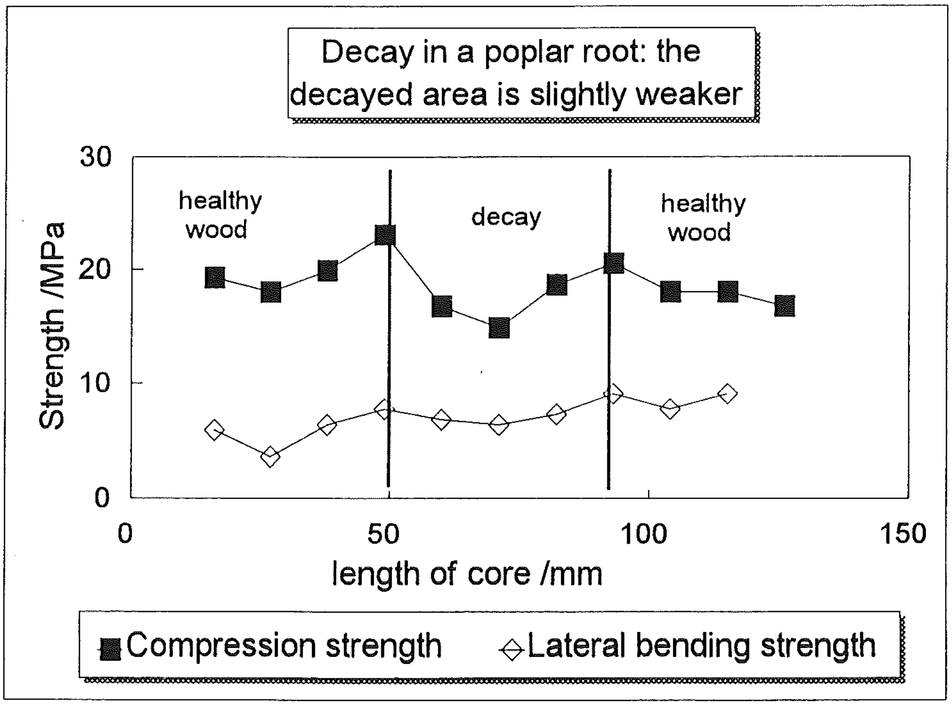
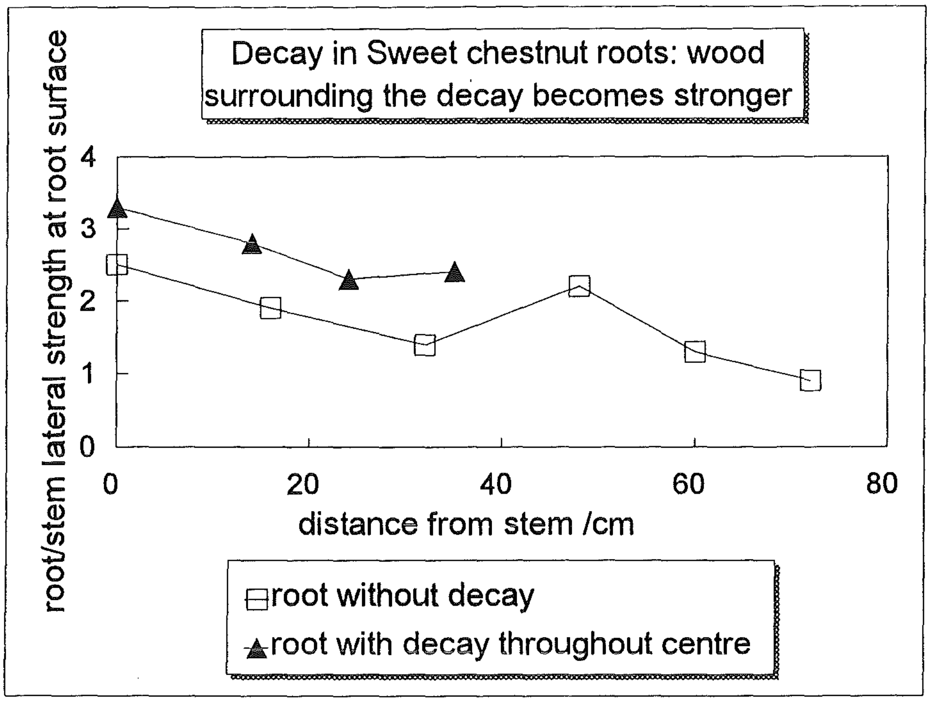


Fig. 3.4



In heart-systems, lateral roots tapered rapidly and were highly branched. The lateral roots of Scots Pine, the only tree with a tap root system found, tapered rapidly but had few branches. The root systems of trees growing in the Palatinian forest were well developed, as the soil was dry with a high proportion of sand, therefore improving drainage. Eight of the Sweet chestnuts examined were decayed in the centre of the stem base and, like the ashes growing on waterlogged ground, had produced a zone of especially strong wood (Fig. 3.5), which was much stronger than the normal wood. Again, the results from these areas were removed for the analysis.

Fig. 3.5



The lateral roots of Norway spruce were growing very close to or on the soil surface, thereby exposing much of the root. In roots of gymnosperms, sapwood and heartwood are usually indistinct. However, in exposed roots, sapwood often forms (Fayle 1968), as in the case of the spruces examined. The compression strength values of sapwood were 5-10 MPa lower than the heartwood (Figs. 3.6, 3.7). However, the lateral bending strength values did not differ between heartwood and sapwood (Fig. 3.7). In the results analysis, the mean of the wood strength across the whole length of each core was used (*i.e.* values for both sapwood and heartwood were taken), so that root strength could be compared with mean stem strength, where sap- and heartwood are highly distinct.

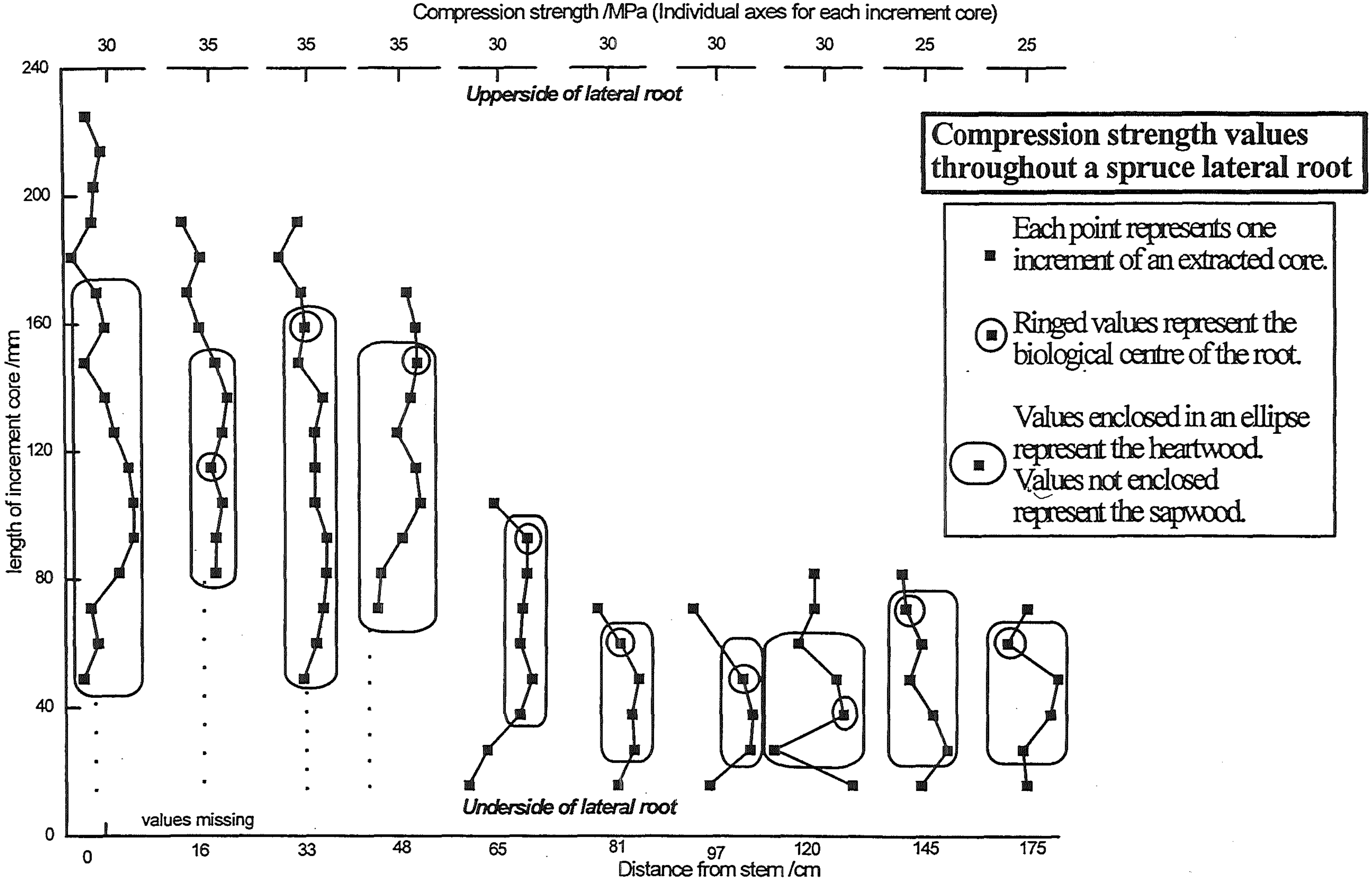
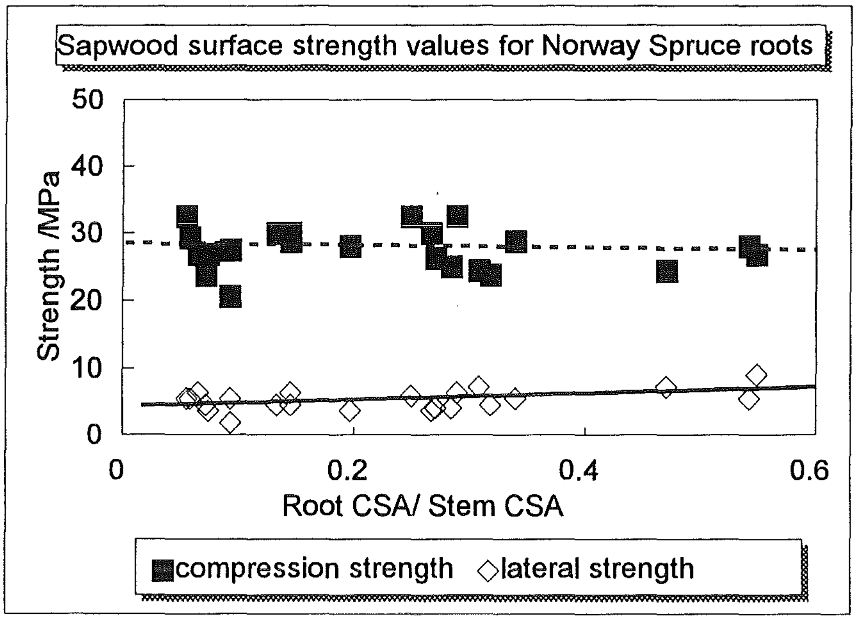

Compression strength /MPa (Individual axes for each increment core)
30
35
35
35
30
30
30
30
25
25
240
200
160
120
80
40
0
length of increment core /mm
Upperside of lateral root
Underside of lateral root
values missing
0
16
33
48
65
81
97
120
145
175
Distance from stem /cm
Compression strength values throughout a spruce lateral root
Each point represents one increment of an extracted core.
Ringed values represent the biological centre of the root.
Values enclosed in an ellipse represent the heartwood. Values not enclosed represent the sapwood.

Fig. 3.6

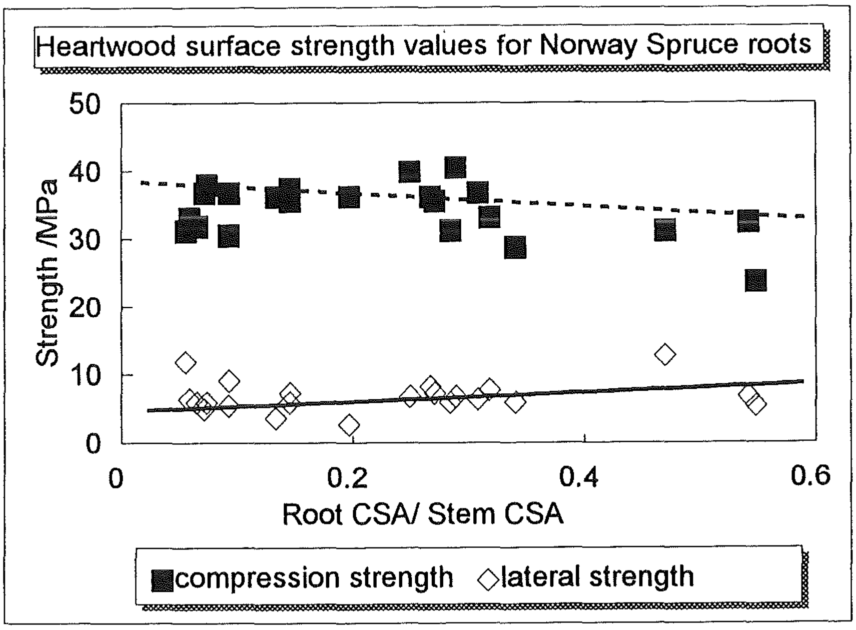
Fig. 3.7



Lateral bending strength:
Y = 2.70 x X + 4.58
$R^2 = 0.07$

Compression strength:
Y = -4.9 x X + 28.6
$R^2 = 0.06$

Fig. 3.8



Lateral bending strength:
Y = 2.20 x X + 6.24
$R^2 = 0.02$

Compression strength:
Y = -10.28 x X + 36.47
$R^2 = 0.16$

3.3 Root strength

Generally root strength decreased along the lateral root and was found to be much greater in hardwoods than softwoods (Tables 3.1).

Table 3.1

Actual values of root strengths for different tree species (MPa)
Values given are the means from the base and tip of the lateral root

		COMPRESSION STRENGTHS		
Type of tree		**Plate**	**Heart**	**Tap**
	Ash	29.1 - 23.9		
ANGIOSPERM:	Poplar	20.2 - 20.6		
	Beech		39.0 - 29.0	
	Sweet chestnut		26.7 - 21.8	
	Norway spruce	29.3 - 24.5		
GYMNOSPERM:	Larch		26.7 - 23.9	
	Scots pine			27.3 - 19.1

		LATERAL BENDING STRENGTHS		
	Ash	15.8 - 8.2		
ANGIOSPERM:	Poplar	7.8 - 3.4		
	Beech		22.5 - 8.4	
	Sweet chestnut		13.2 - 7.2	
	Norway spruce	8.6 - 4.8		
GYMNOSPERM:	Larch		6.31 - 3.8	
	Scots pine			4.9 - 2.5

In order to compare strength distribution along lateral roots between trees of different sizes and species, the mean strengths (in gymnosperm species: both lateral bending and compression; in angiosperm species: only the surface values of lateral bending strength) of each wood core were taken and divided by the mean strength of the stem at breast height. Abnormal wood strength values *e.g.* for decayed wood, were ignored. Lateral bending strength and axial compression strength decreased with increasing distance from the stem in all tree species examined (Tables 3.2, 3.3, Fig. 3.9, 3.10). The extent to which strength was reduced along the root differed depending on the type of root system the tree possessed. In species with tap (Scots pine) and heart-shaped systems (beech, larch, Sweet chestnut), both lateral and compression strength decreased at a faster rate along the length of the 1°L's compared to those of plate systems (poplar, ash, Norway spruce).

Strength decreased along the 1°L's at a similar rate to that measured in roots of heart and tap systems.

Table 3.3

Linear regression equations for each species when root/stem compression strength is plotted against distance of the sample from the stem.

Type of root system		Regression equation	R^2	P
PLATE	Norway spruce	$Y = -0.001 \times X + 1.09$	0.48	< 0.001
	Poplar	$Y = 0.003 \times X + 0.92$	0.21	0.066
	Common ash	$Y = -0.002 \times X + 0.85$	0.80	< 0.001
HEART	Larch	$Y = -0.002 \times X + 0.97$	0.60	< 0.001
	Beech	$Y = -0.002 \times X + 1.08$	0.87	< 0.001
	Sweet chestnut	$Y = -0.004 \times X + 0.90$	0.97	< 0.001
TAP	Scots pine	$Y = -0.004 \times X + 0.92$	0.91	< 0.001

Fig. 3.9

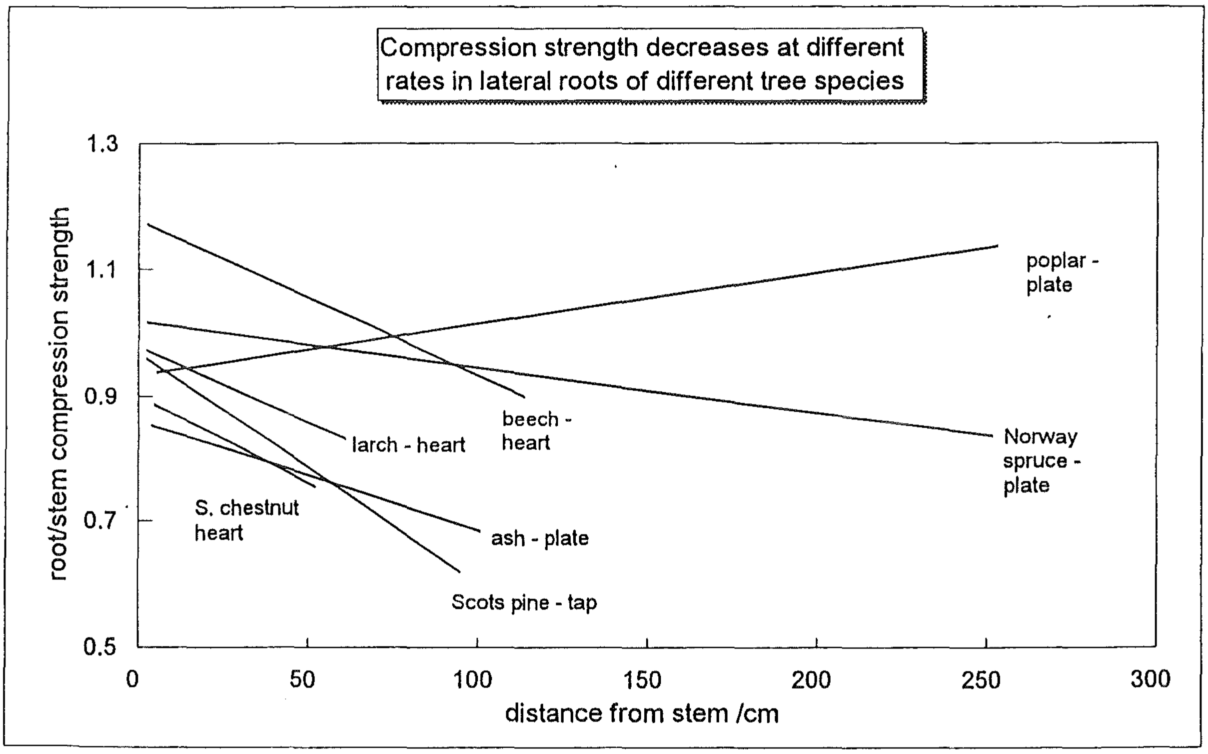
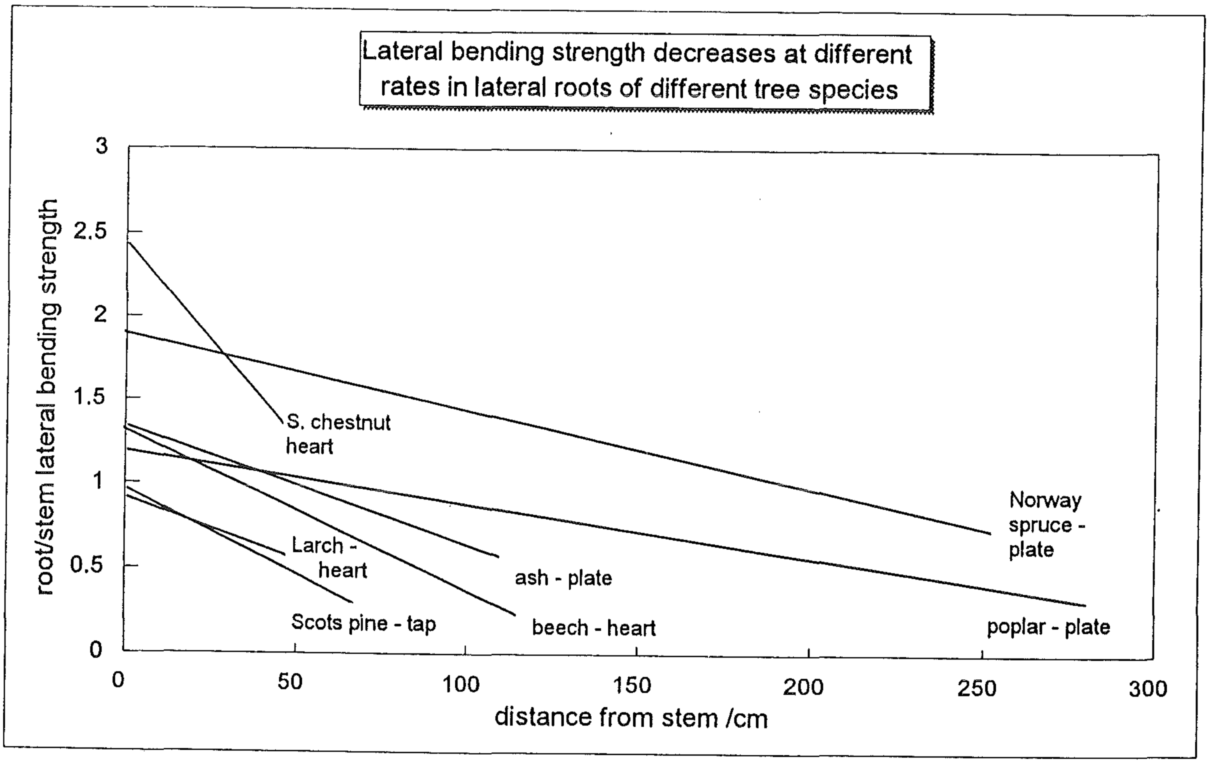


Table 3.4

Linear regression equations for each species when root/stem lateral strength is plotted against distance of the sample from the stem.

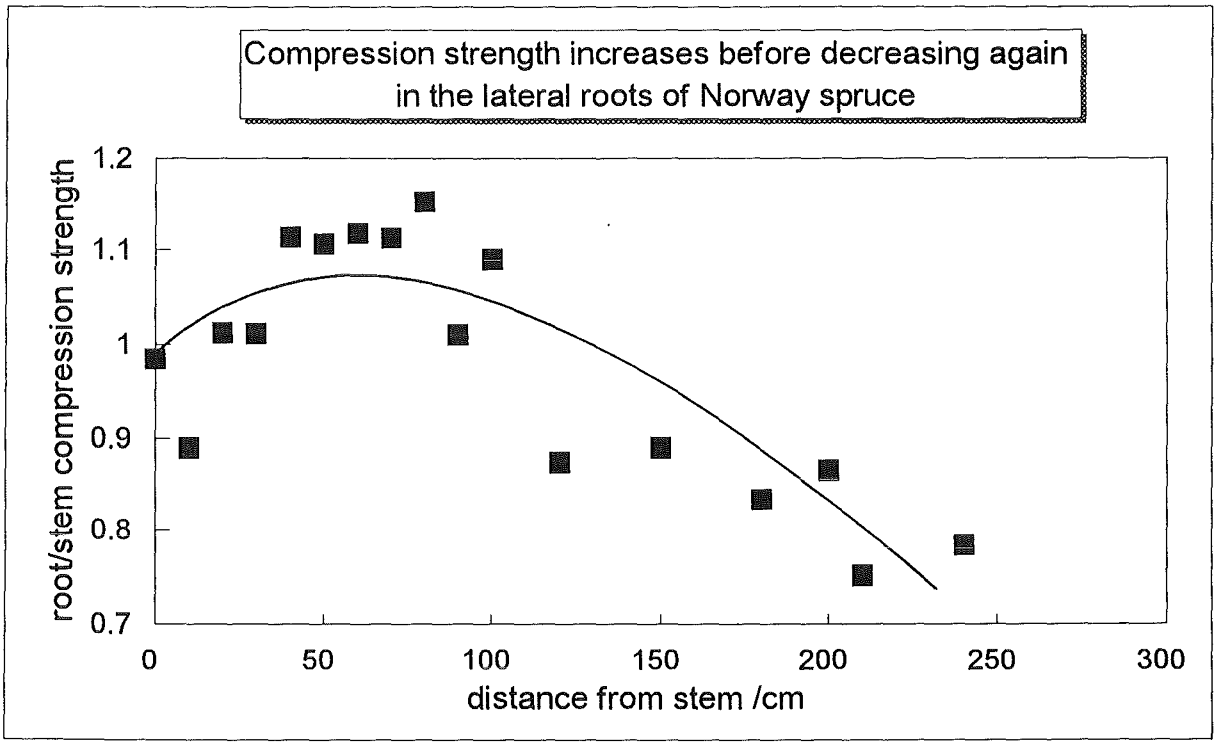
Type of root system		Regression equation	R^2	P
PLATE	Norway spruce	Y = -0.004 x X + 1.81	0.64	< 0.001
	Poplar	Y = -0.002 x X + 1.26	0.49	< 0.001
	Common ash	Y = -0.005 x X + 1.34	0.61	< 0.001
HEART	Larch	Y = - 0.006 x X + 0.94	0.93	< 0.001
	Beech	Y = - 0.009 x X + 1.39	0.92	< 0.001
	Sweet chestnut	Y = - 0.026 x X + 2.38	0.98	< 0.001
TAP	Scots pine	Y = - 0.074 x X + 0.96	0.85	< 0.001

Fig. 3.10



In the 1°L's of poplar and Norway spruce, compression strength was found to increase at a certain distance from the stem before decreasing again. Second order polynomial regressions of compression strength against distance are highly significant and show that in Norway spruce, the maximum increase in strength was found 0.5 - 1 m from the stem (Fig. 3.11 whereas in poplar, the maximum was found at a distance of 1 - 2 m from the stem (Fig. 3.12).

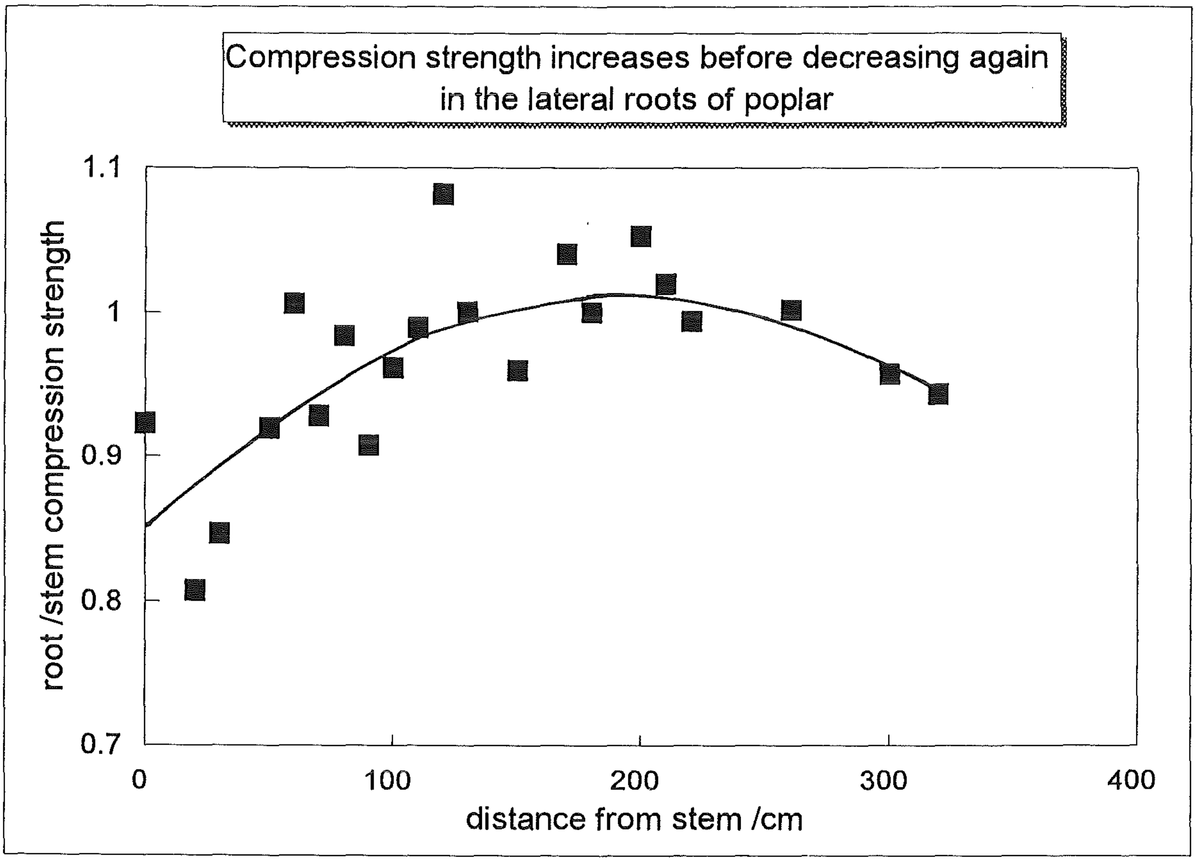
Fig. 3.11



$Y = 0.00168 \times X + 0.85 + (-4.291E - 006) \times X^2$

$R^2 = 0.56, P = 0.036$

Fig. 3.12



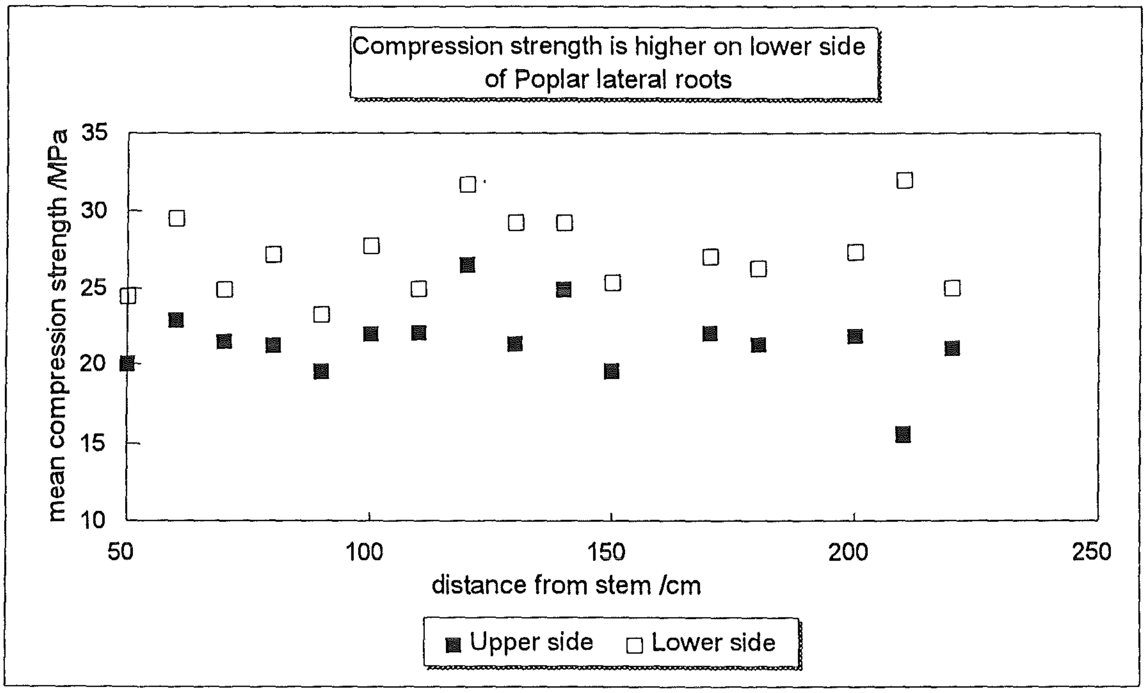
$Y = 0.0015 \times X + 1.00037 + (-1.1642E - 005) \times X^2$

$R^2 = 0.66, P = 0.09$

3.4 Strength distribution within lateral roots

In poplar sp. growing on flat wet ground, a T-test showed that compression strength was found to be significantly greater by approximately 25 % on the underside of the 1 L's (Fig. 3.13, $P_{16,1,}$ = 0.007). This increase does not gradually occur throughout the root but is a sharp increase which occurs in the lowermost 1-2 cms of the 1 L (Fig. 3.14). This sudden increase in strength was not observed in any other species examined.

Fig. 3.13



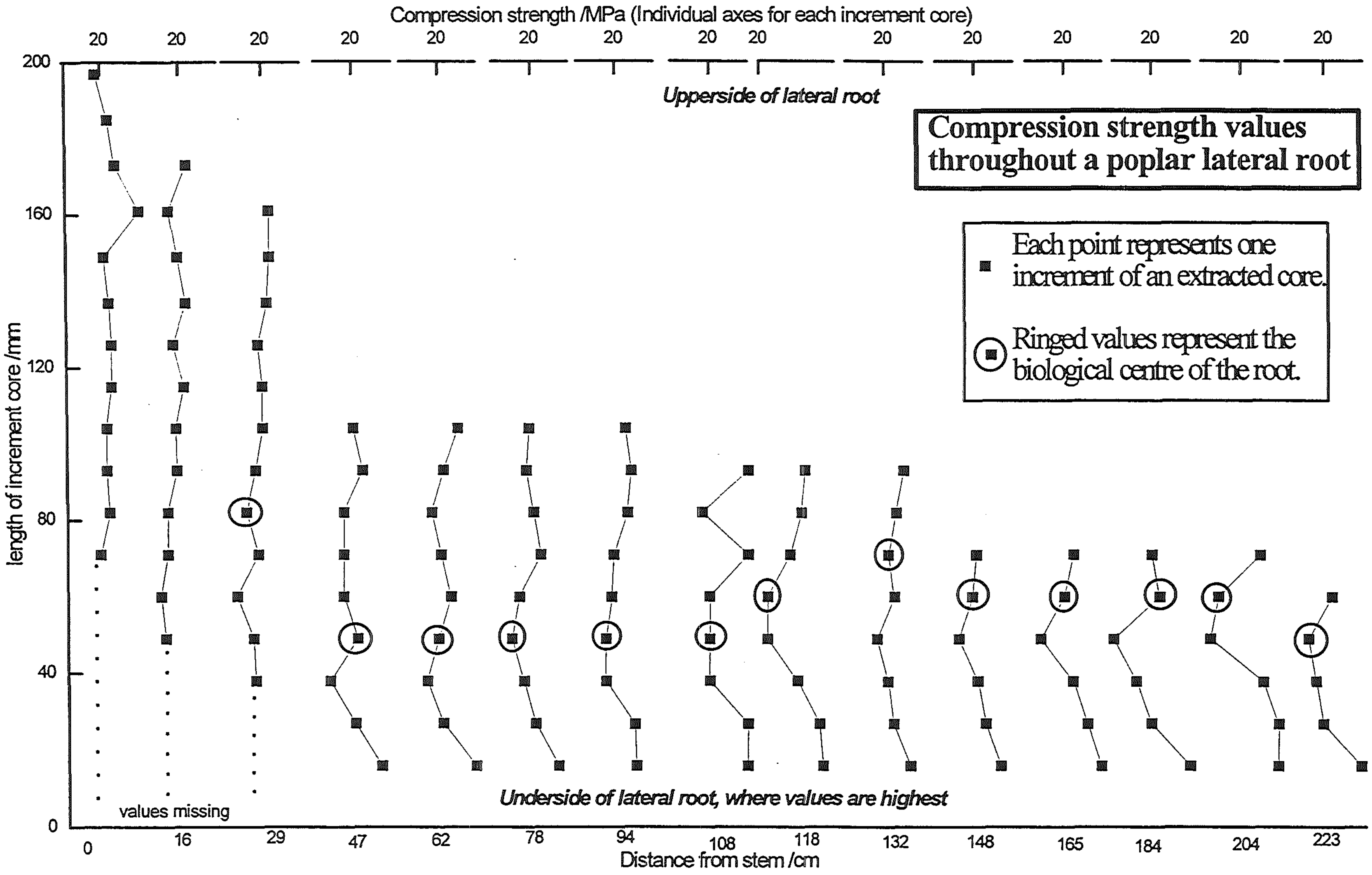

Compression strength /MPa (Individual axes for each increment core)
20
20
20
20
20
20
20
20
20
20
20
20
20
20
20
Compression strength values throughout a poplar lateral root
Upperside of lateral root
Each point represents one increment of an extracted core.
Ringed values represent the biological centre of the root.
length of increment core /mm
200
160
120
80
40
0
values missing
Underside of lateral root, where values are highest
0
16
29
47
62
78
94
108
118
132
148
165
184
204
223
Distance from stem /cm

Fig. 3.14

3.5 Investment in lateral bending strength

In order to determine the investment in lateral bending strength compared to that in compression strength, the former was divided by compression strength (A. Zipse, pers. comm. Table 3.4) and regressed with the distance from the stem (Table 3.5, Fig. 3.15). The range of values obtained for each species varied, with angiosperms investing greater energy in lateral bending strength compared to gymnosperms. The largest values were found at the root-stem joint where lateral bending stresses are highest. The values then decreased linearly with distance from the stem, except in Norway spruce and poplar. In these two species, lateral bending: compression strength decreased rapidly in the first 1 m away from the stem, and in Norway spruce, even appeared to increase with distance. These curves were highly significant and described by third order polynomial regressions (Fig. 3.16, Fig. 3.17), and are probably due to the high values of compression strength found in the 1°L's of these trees with plate systems.

Table 3.5

Range of values showing investment in lateral bending strength
(the values given are from the stem-root joint and the end of the 1°L)

Type of tree		Range of values for each tree species Plate	Heart	Tap
	Ash	0.42-0.44		
ANGIOSPERM:	Poplar	0.39-0.15		
	Beech		0.58-0.29	
	Sweet chestnut		0.49-0.33	
	Norway spruce	0.29-0.20		
GYMNOSPERM:	Larch		0.24-0.07	
	Scots pine			0.18-0.131

Table 3.4

Linear regression equations for each species when root lateral/compression strength is plotted against distance of the sample from the stem.

Type of root system		Regression equation	R^2	P
PLATE	Norway spruce	Y = -0.000 x X + 0.20	0.05	0.120
	Poplar	Y = -0.001 x X + 0.32	0.71	< 0.001
	Common ash	Y = -0.000 x X + 0.39	0.38?	0.002
HEART	Larch	Y = - 0.002 x X + 0.23	0.95	< 0.001
	Beech	Y = - 0.003 x X + 0.51	0.87	< 0.001
	Sweet chestnut	Y = - 0.004 x X + 0.50	0.98	< 0.001
TAP	Scots pine	Y = - 0.001 x X + 0.17	0.45	< 0.001

Fig. 3.15

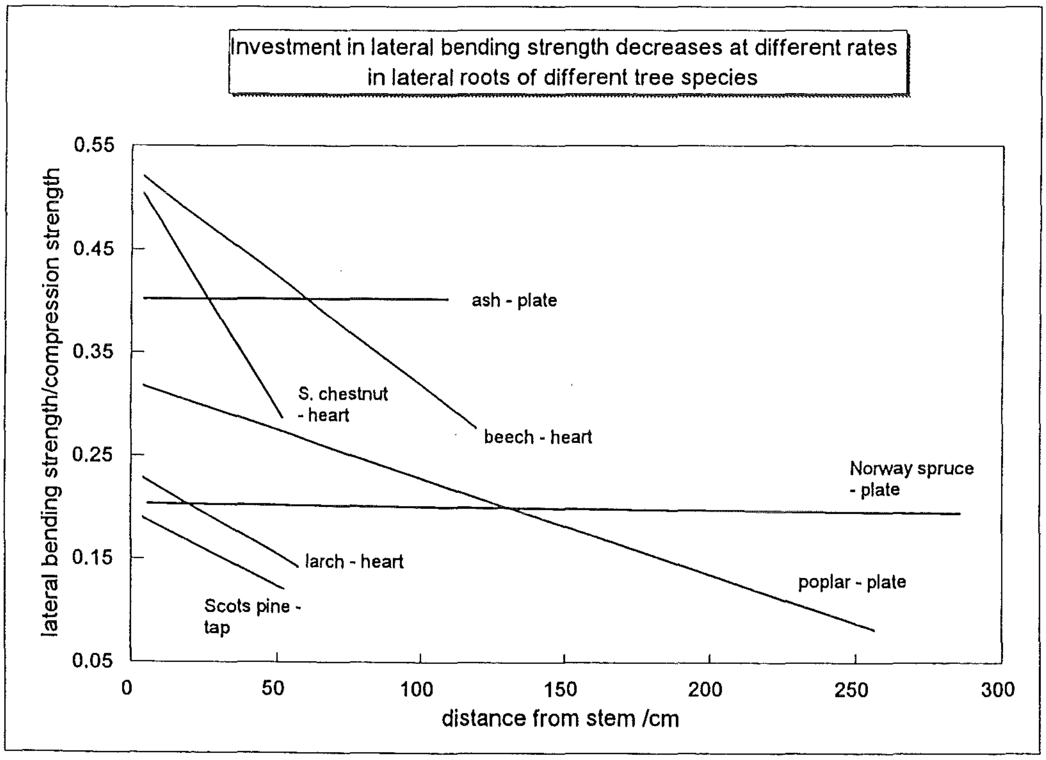
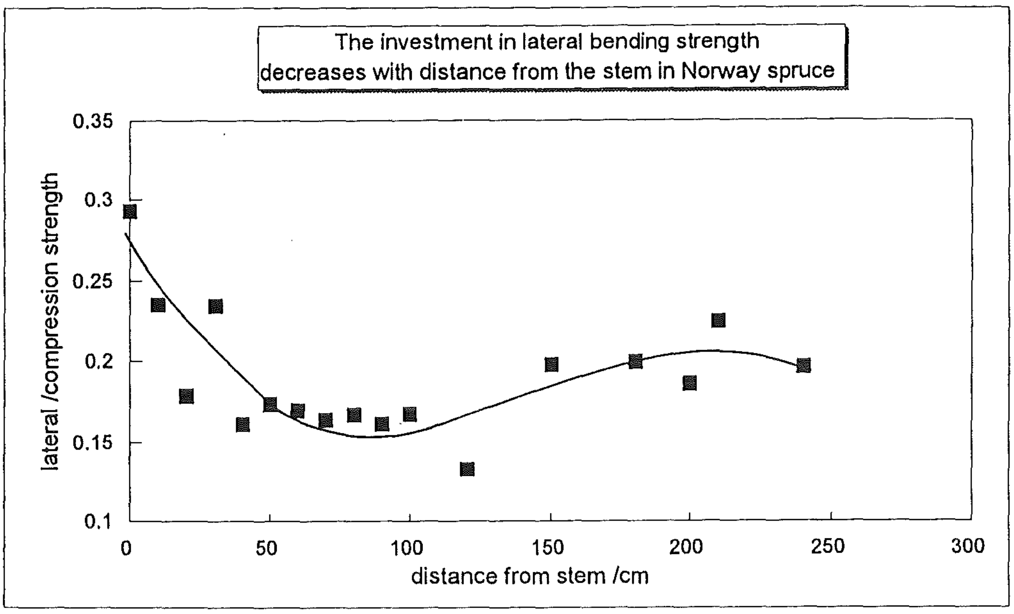
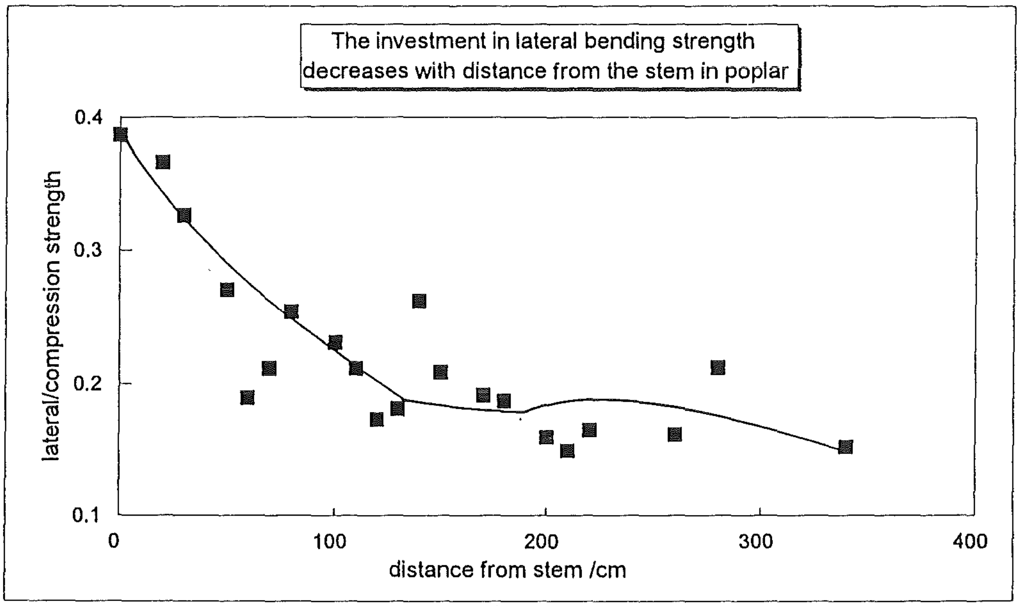


Fig. 3.16



$$Y = 0.388 - 0.00287 \times X + 1.30604E - 005 \times X^2 + (- 1.95545E - 008) \times X^3$$
$R^2 = 0.81$, $P = 0.18$

Fig. 3.17



$$Y = 0.27161 - 0.0031 \times X + 2.49778E - 005 \times X^2 + (-5.59865E - 008) \times X^3$$
$R^2 = 0.74$, $P = 0.006$

3.6 Prediction of root strength

3.6.1 Healthy roots

In order to predict wood strength in healthy roots, graphs have been constructed (Appendix A), which give an estimate of wood strength for a particular size of root at a certain distance from the stem. The range of lateral bending and compression strength values were determined using a linear regression of rootwood/stemwood strength against distance from the stem. This line was plotted on the graph and then the mean standard error of variation of wood strength between the ten roots was calculated and plotted either side of the regression line. Therefore a range was created (shaded areas on graphs), in which healthy wood values should lie. The minimum and maximum values of lateral root CSA measured, were also plotted on the graph for each sampling point along the root. If root CSA lies outside this range, the wood strength values may not be reliable, so should be treated with caution.

3.6.2. Decayed roots

Values of wood strength in areas of decay are usually very low *e.g.* in the decayed centre of a Sweet chestnut root, the lateral bending strength was almost zero (Fig. 3.18). The healthy wood which surrounds the decayed area is often much stronger than normal wood in order to compensate for the loss of strength in the decayed wood. In two lateral roots of Norway spruce (both roots were of a similar CSA and growing on the same tree), one root with decay in the centre at the stem-root joint, had values for lateral bending strength which were over 50 % greater at the root surface than in the healthy root (Fig. 3.19). Further along the roots, where no decay was present, strength values were very similar between the two roots. Compression strength values were very similar along the whole length of both roots.

Fig. 3.18

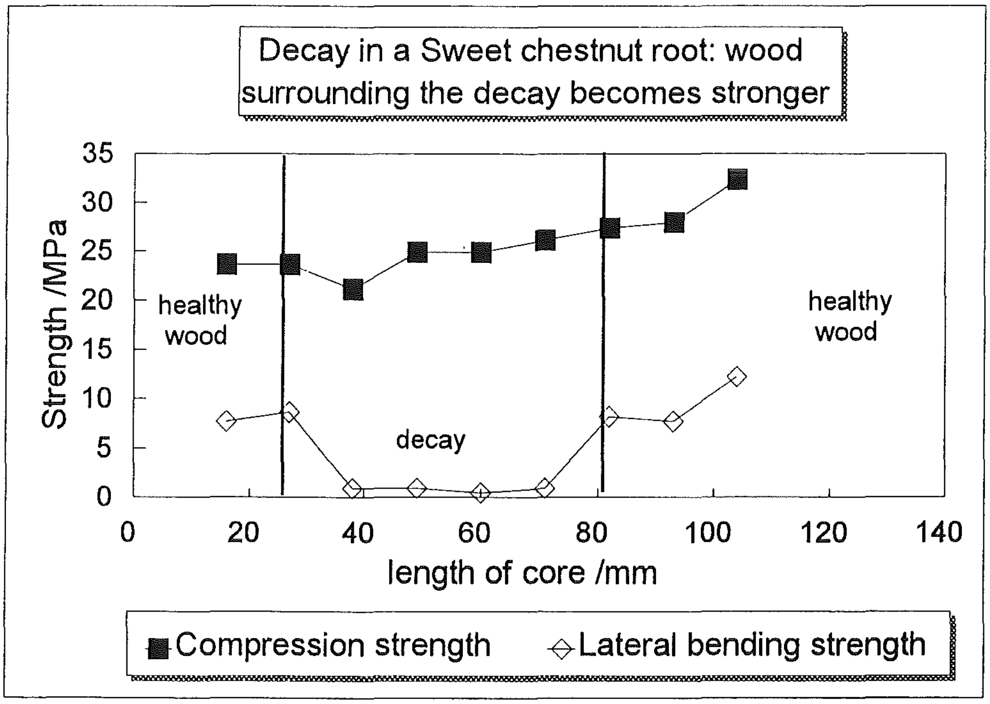
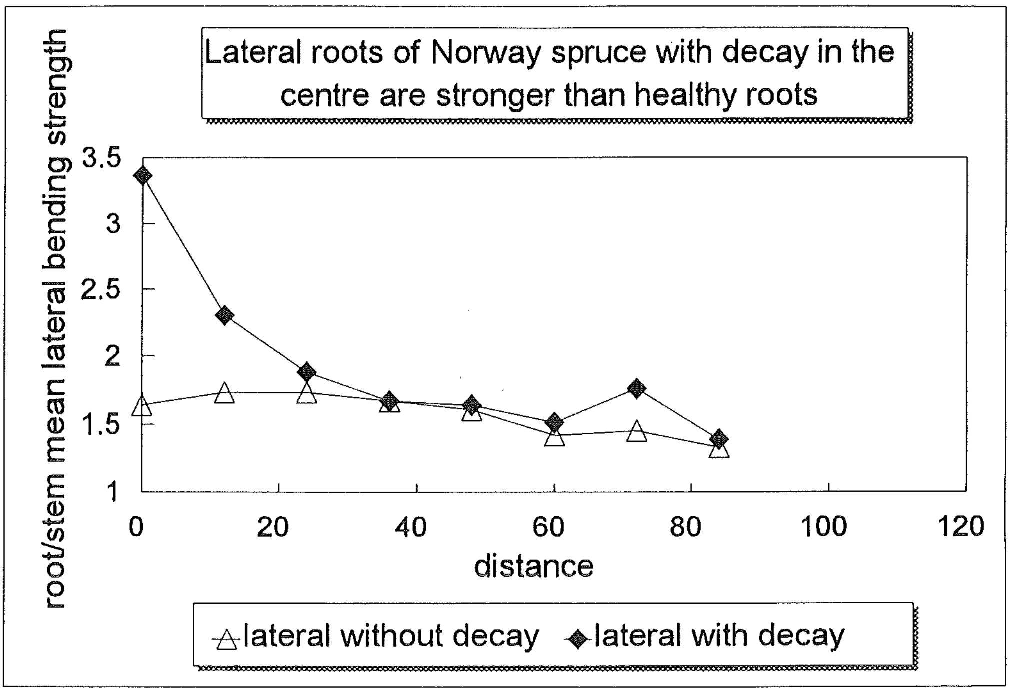


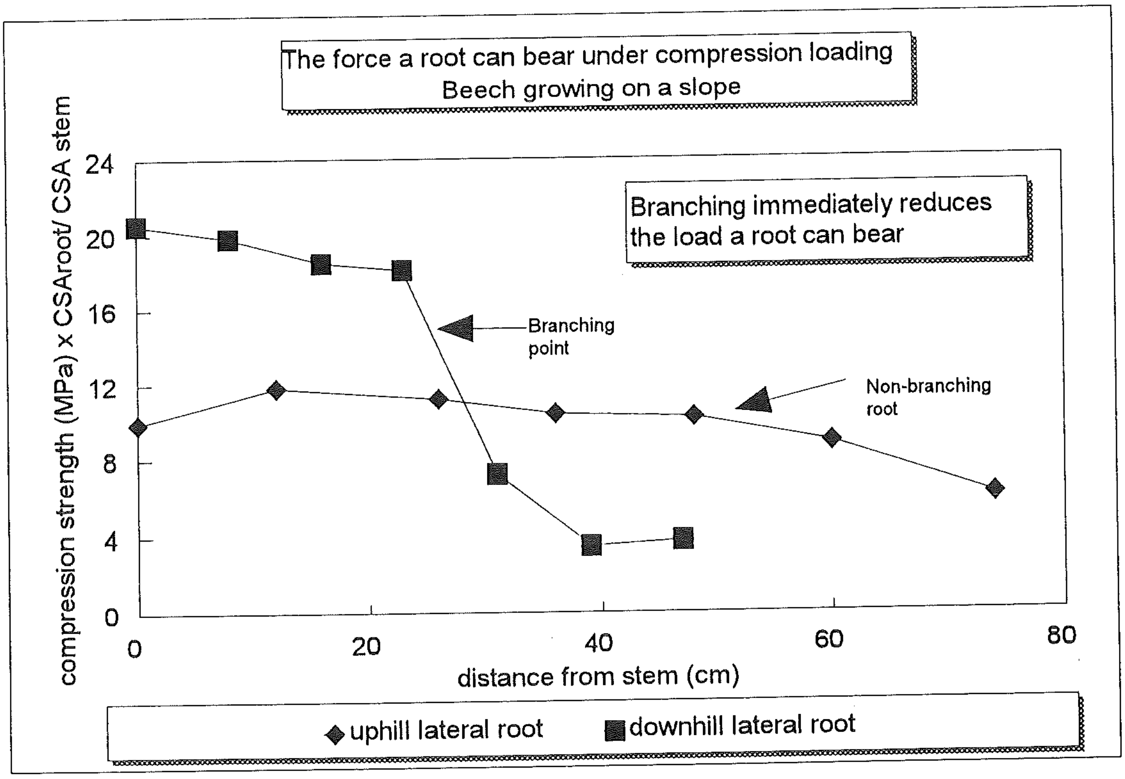
Fig. 3.19



3.7 Effect of branching on load bearing roots

To calculate the force a root can bear under compression loading, the compression strength values can be multiplied by root CSA/stemCSA. As a root branches, the CSA is reduced, therefore the load bearing capacity also decreases (Fig. 3.20).

Fig. 3.20



3.8 Roots growing on slopes

Lateral roots growing downhill are subjected to a greater compressive loading than roots growing uphill or perpendicular to the slope direction. It is relatively difficult to find lateral roots growing in all three directions on the same tree, however, in one Norway spruce a very symmetrical root system was found, so compression strength values could be compared between the three roots. The downhill lateral root buttress had 25 % greater root/stem compression strength than the roots uphill or perpendicular to the slope direction (Fig. 3.21). One beech tree with up- and downhill lateral roots were also examined. The root/stem compression strength was higher in the first 60 cm of root than the other roots (Fig. 3.22). There were no differences in lateral bending strength between roots growing up- and downhill in either beech or Norway spruce.

Fig. 3.21

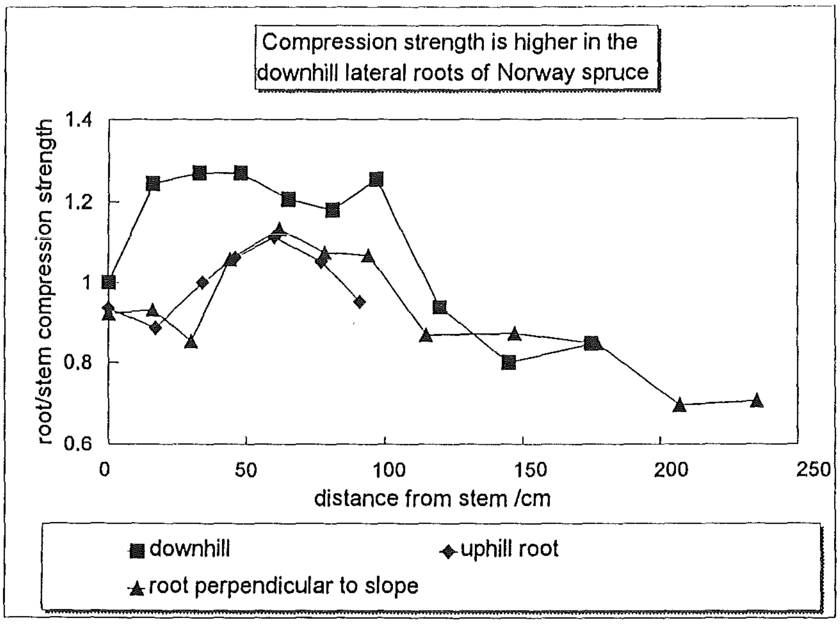
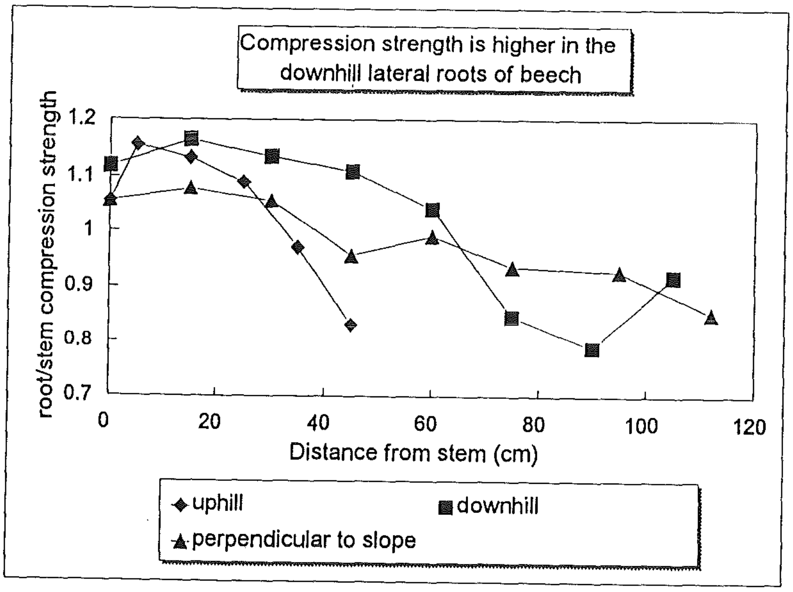


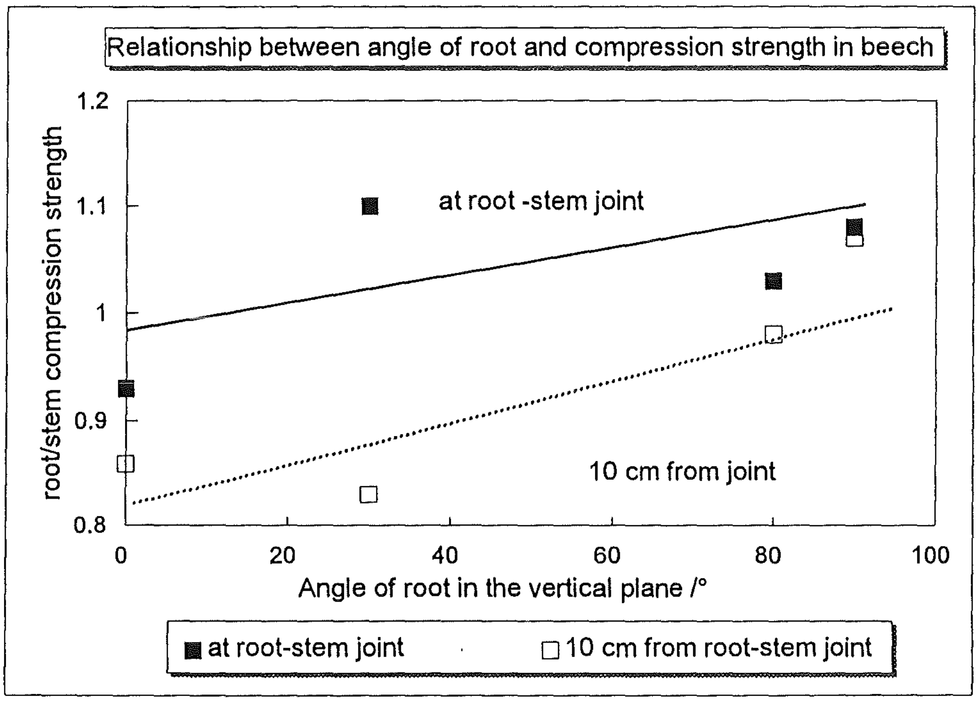
Fig. 3.22



3.9 Comparison of strength between lateral and sinker roots

Due to the difficulty in obtaining values from sinker roots *i.e.* turning the increment borer without being obstructed by other roots, very few values for sinker roots were obtained. Compression strength values in sinker roots of Scots pine were similar to those in the lateral root at the same distance from the stem, however, in beech, mean compression strength in sinker roots was found to be higher than in the lateral root, at the root-stem joint and at 10 cm from the joint. The angle of the root in the horizontal plane significantly regressed with compression strength (Fig. 3.23) which showed that the more oblique the root, the greater the compression strength. However, these results are based on only four roots, so more data should be obtained in order to confidently say that sinkers are stronger than lateral roots.

Fig. 3.24



At root stem joint: $Y = 0.001 \times X + 0.98$, $R^2 = 0.36$, $P < 0.001$

At 10 cm from joint: $Y = 0.002 \times X + 0.82$, $R^2 = 0.79$, $P < 0.001$

4.1 DISCUSSION

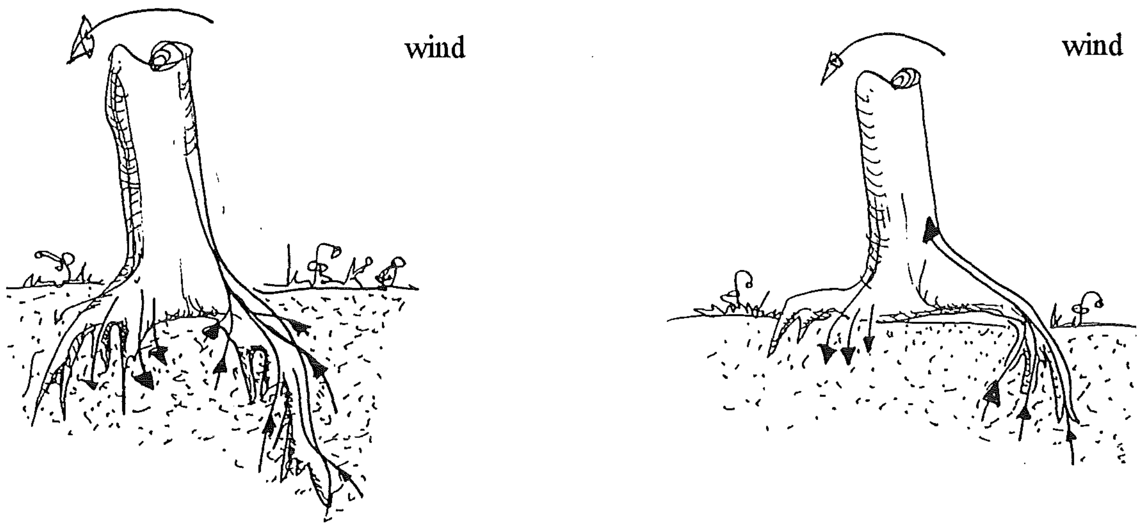
The examination of root strength between different trees show that individual species invest a particular amount of resources to rootwood, depending on the local conditions and type of root system present. Lateral bending strength is less important in the root system than in the stem, as roots are subjected to fewer bending forces. As the roots are under a permanent compressive loading from the weight of the tree, measurement of compression strength was a good indicator of mechanical stress and how the root adapted to that stress. Lateral roots of plate root systems, which grow on or very close to the surface of the ground, will experience more bending and compressive stresses than roots of heart or tap systems, which are usually buried deeper in the ground. Generally, compression and bending strength of lateral roots decreased with increasing distance from the stem which was probably a function of root anatomy. Species with plate systems were relatively stronger further along the lateral root compared to roots from heart or tap systems.

Tree stability is enhanced when external loading forces can be smoothly and quickly dissipated into the ground. In heart root systems, this is achieved by a large surface area due to the higher branching density (Fig. 4.1a). When a lateral root branches, the stiffness of that root is reduced, so it is unable to bear as much load. Therefore, in a highly branched root system, a high density of roots per unit area of soil may be desirable for better anchorage, so that tension can be transferred rapidly to the soil, before root pull-out or breakage occurs (Wu 1976, Ennos 1990). Stability will be further increased when a root branches, due to the weight of the soil which will be lifted up if the tree overturns. Stokes *et al.* (1995c) found that model roots which bifurcated (*i.e.* not at the root-stem joint) with an angle of 60 in the horizontal plane, had the greatest resistance to uprooting, compared to unbranched and roots with smaller or greater branching angles. At this angle, a plate of soil is lifted up at the crux of the branched fork, thereby effectively increasing the root-soil weight resistance of that root. A study of the branching angles in woody root systems of 20 year old it Sitka spruce (*Picea sitchensis*) revealed that the mean branching angle was 58 , therefore, in this system, branching angles are optimized in terms of maximum stability (Stokes *et al.* 1995c). In older spruce trees, the rate of branching per unit area of soil decreases (Coutts 1987, Gruber 1994), therefore the mechanics of anchorage will alter.

As there is a lesser degree of branching in tap and plate root systems, external loading forces must be transferred along the shortest route into the ground to prevent the tree overturning. In the presence of a large tap root or vertical sinkers, this is achieved near the stem. However, if sinker roots are few, or are thin and weak, forces must travel further along the lateral root before being dissipated into the ground (Fig. 4.1b). Therefore, lateral roots in shallow plate systems of Norway spruce and poplar are subjected to higher stresses and so a greater investment in wood strength would help resist loading on the root system.

Fig. 4.1

Forces are dissipated into the ground nearer the stem in heart root systems compared to plate systems


a) Heart root system

b) Plate root system

Compression and bending strengths in the lateral roots were generally lower than that in the stem. Changes in root anatomy along the lateral roots are probably responsible for the decrease in strength observed. In ring porous hardwoods, the most striking change in anatomy from stem to root, is that the root becomes diffuse porous. This reaction appears to be light responsive, as when Lebedenko (1962) exposed diffuse porous Sweet chestnut roots to light, they became ring porous again. Cells of lateral roots become larger and longer with thinner, less lignified cell walls and the number of cells per growth ring and vessels per unit area decreases with increasing distance from the stem (Table 4.1) (Fayle 1968). The increase in cell size and decrease in cell wall thickness, coupled with the change in porosity, will probably produce a more rapid decrease in the strength of lateral roots of ring porous hardwood than softwood trees. The regression coefficients of strength against distance from the stem (Tables 3.1, 3.2) for the ring porous hardwoods (ash, Sweet chestnut) were higher than those of other trees in the same category. However, Scots pine, a softwood, had the highest regression coefficient of both compression and bending strength for all tree types, therefore there must exist another factor influencing the mechanical strength of lateral roots. In an examination of three different coniferous species, Seibt (1964), found that cell density in the root base of *Pinus* (pine) was less dense than that in the stem and of *Picea* (spruce), more dense. The root cell density of *Larix* (larch) was similar to that of the stem. Seibt attributed this to the type of root system, as in plate systems (*Picea*) there are greater mechanical demands nearer the stem than in tap or heart systems (*Pinus* and *Larix* sp. respectively). Therefore, it appears that mechanical requirements may also influence rootwood anatomy which in turn determines the strength of the root.

ROOT ANATOMY

STEM/BUTTRESS → ROOT → ROOT TIP

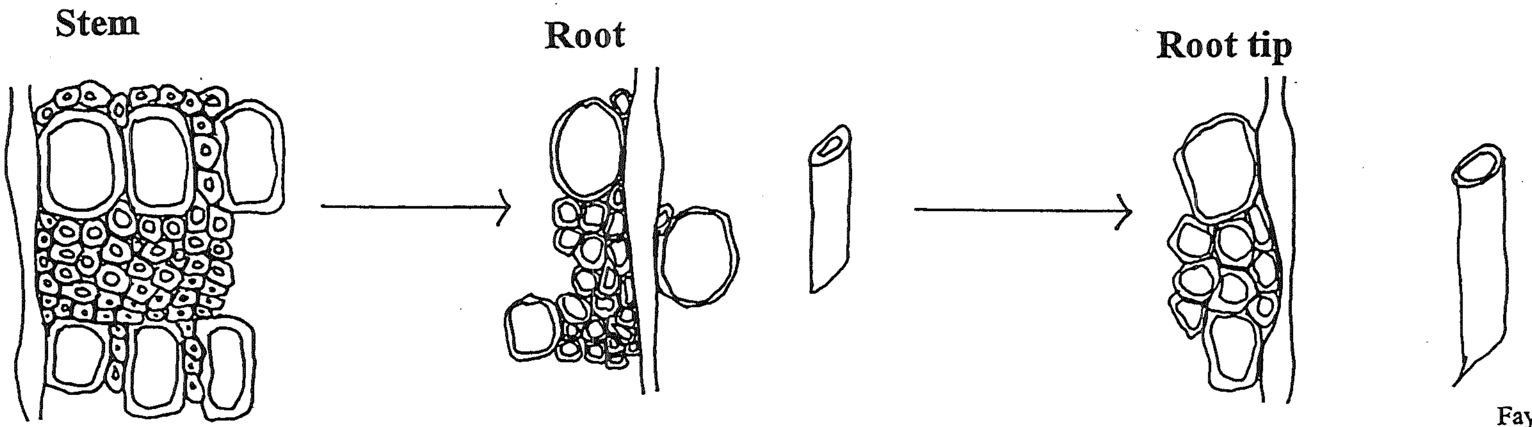
Cells become larger
Cell walls become thinner
Cell walls are less lignified
Growth rings have less cells
Number of vessels per unit area is less
Pith is absent

→

In hardwoods, the wood changes from ring porous to diffuse porous
(appears to be light-responsive)

Cell length & diameter increase
Cell walls become thinner
Young roots (< 16 years old) have little summer wood

Table 4.1



Fayle (1968)

Generally, in the trees with heart or tap root systems, lateral bending strength was similar or slightly higher at the root-stem joint than in the stem but beyond this point, it rapidly decreased. However, trees with plate root systems *i.e.* Norway spruce, poplar and ash, had a higher lateral bending strength in the root than in the stem up to approximately 1 m from the stem. Sweet chestnut lateral roots were only sampled up to 50 cm from the stem but were approximately twice as strong as the stem. It is not known why so much energy is invested into lateral bending strength of Sweet chestnut roots, but it may be at the expense of the stem which is intrinsically weak. Although strength values of abnormal wood were removed from the analysis, it is possible that the high values for lateral bending strength in Sweet chestnut roots may have occurred as a response to decay deeper in the tree. Wound associated tissue, even far away from the wound, is distinctly different to normal wood tissue. Cell walls (including those of wood rays) become thicker and vessel production is retarded (Shigo 1972, Sharon 1973). Such changes in wood anatomy will be reflected in strength values. In wound associated tissue at the root-stem base in Norway spruce, lateral bending strength values were twice as high as that in a nearby healthy root of a similar size.

Most trees probably have a higher lateral bending strength at and near the stem base because this is the area of highest bending stress (Albrecht *et al.* 1995). External forces such as wind will be transmitted down the stem to the buttressing zone before being transferred into the ground. The flow of the force will be more smoothly transmitted into the ground if the angle between the root and stem is curved, *i.e.* with a buttress, normally found in plate systems, or with roots growing obliquely into the ground, as often found in heart systems. In Scots pine, the angle between the stem and lateral root was quite sharp, but less forces are probably transmitted at this point as the force-flow will take a more direct path down the large tap root.

The angiosperm species invested 30 - 55 % resources into root lateral bending strength at the root-stem base, whereas gymnosperms invested only 15 - 25 %. Lateral strength has recently been related to the presence of the radially spreading lignified wood rays (Mattheck *et al.* 1994). Compression tests carried out by Myer (1922) and Easterling *et al.* (1982) show that the volume of rays is more important for strength than the size or number per unit area present. Myer's colleague, DeSmidt (1922) found that in *Ulmus fulva,* ray volume was maximal at the root-stem base and in the root, which was confirmed by Harlow (1927) in *Thuya occidentalis.* Therefore, the increase in strength at the root-stem base can be attributed to the increase in ray volume, as suggested by Albrecht *et al.* (1994). Using Schweingruber's (1990) description of ray type and Myer's (1922) and Bannan's (1937) extensive lists of ray content in commercial forest trees, the approximate ray volume between species can be compared and related to their lateral bending strenth, assuming a proportional relationship between stem and roots exists. Coniferous species usually have uniserate rays (one cell wide), therefore the number of rays can also be used to describe volume. Spruce has the greatest number in the roots, with 37 mm^{-1} present, compared to pine and larch species which have a content of 28 mm^{-1} and 26 mm^{-1} respectively. These ray volumes appear to correlate with bending strength values, as Norway spruce had a bending strength value of 8.6 MPa in Spruce to 6.3 and 4.9 MPa in larch and Scots pine, respectively. The ray volume occupies 6 - 11 % of coniferous stem wood, whereas hardwoods possess a much higher and more variable ray volume. The rays in poplar and chestnut species are normally uniserate and make up only approx. 11 % of the stem wood. Bi- and triserate rays (two and three cells wide) can be found in ash and make up approx. 14 % of the stem wood volume. Beech trees have the highest ray volume, made up of large multiserate rays (up to 20 cells wide). The ray volume can therefore be directly correlated to the actual lateral bending strength values measured at the lateral root-stem base, as beech had the highest values (22.5 MPa). Ash was found to be the next strongest (15.8 MPa), followed by Sweet chestnut (13.2 MPa) and poplar (7.8 MPa).

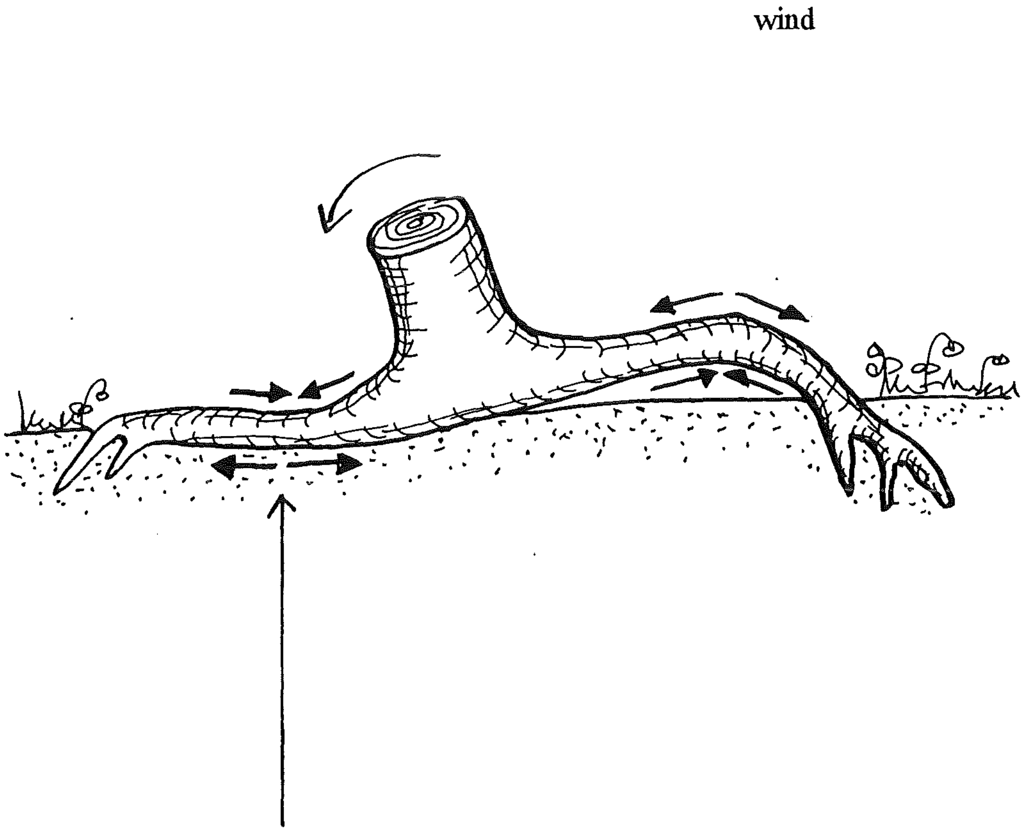
Although the lateral bending strength values differed enormously between soft- and hardwoods, compression strength was quite similar, with beech as the only species where strength was found to be much higher, possibly due to the presence of multiserate rays. Compressive and tensile strength is related to ray content, but more importantly, to cell density, *i.e.* cell number, size, cell wall thickness (Kellogg & Ifju 1962, Easterling *et al.* 1982). The poplar species had a lower compression strength than both hard- and softwoods, which must be due to the diffuse porous nature of the wood and the cell structure. Compared to beech, also a diffuse porous species, poplars have a much lower cell density (see Schweingruber 1990). Although vessel size seems to be similar between the two genera, xylem cells of poplar appear to be larger with thinner cell walls.

The properties of the cell wall material also determine strength, such as lignin and cellulose content (Hale & Clermont 1963). Lignin acts as a bulking agent and can increase the compressive strength of cell walls. It helps prevent water from infiltrating and thus reduces the elastic and shear moduli of the cell wall. Cellulose, as a crystalline chain which deforms little in tension, has a tensile strength equal or greater than many steels, although steel is several times denser than cellulose (Niklas 1992). There may be differences in lignin and cellulose content of the cell wall between the tree species examined, which may further explain the differences found in wood strength.

The investment in root compression strength compared to that in the stem varied much less than the bending strength between species. At the root-stem joint, compression strength was similar to that in the stem at DBH for all species except beech, where it was found to be slightly higher, again probably due to the increase in ray volume. This lack of variation in compression strength suggests that cell density does not increase in the buttress region. However, in the lateral roots of poplar and Norway spruce, compression strength was found to increase along the root, *i.e.* at 0.25 - 0.5 m in spruce and 1.5 - 2 m in poplar, before decreasing again, suggesting changes in root anatomy have occurred. As a tree bends in the wind, the lateral roots on the leeward side will be pushed downwards and compressed onto the hard bearing surface of the soil. Windward roots will be pulled upwards and held in tension, the point at which maximum bending occurs being much further away from the stem (Fig. 4.2). The region in which maximum strength occurs along the root may therefore also coincide with the position of the leeward hinge.

Fig. 4.2

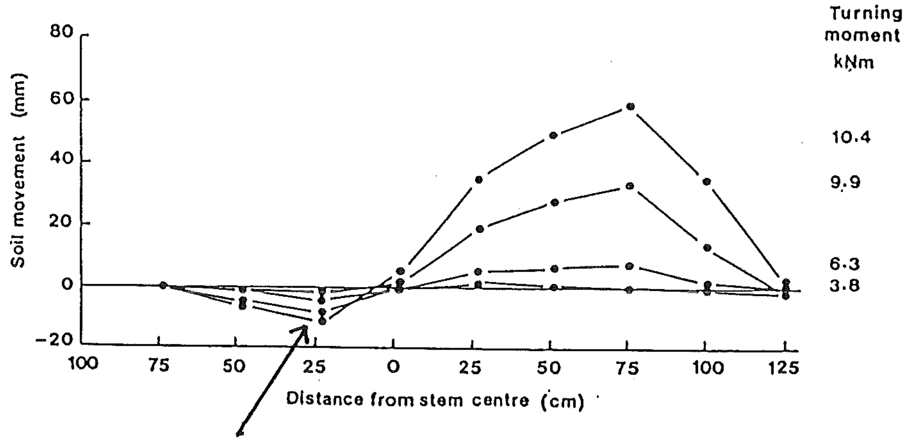
Windward roots are lifted up whereas the leeward roots are pushed down on to the bearing surface of the soil



However, in such large trees, a momentum will build up in the stem, causing it to sway strongly (Milne 1988), therefore, lateral roots on all sides will be held alternately in tension and compression. In Sitka spruce of a similar age and size to the Norway spruce and poplar examined in this study, Coutts (1983, 1986) examined the displacement of the root-soil plate when a horizontal force was applied to the stem. The maximum depression of the soil surface occurred at 25 cm on the leeward side and at 75 cm from the stem on the windward side (Fig. 4.3).

Fig. 4.3

Displacement of the root-soil plate when a horizontal force was applied to the stem of Sitka spruce (Coutts 1986)



leeward hinge (point of rotation)

As the highest measured compression strength occurred at 25 - 50 cm from the stem in Norway spruce, it probably occurs somewhere between the points of maximum bending when the lateral root is held alternately in compression and tension. In 1937, a German botanist, Riedl, found that in 12 cm diameter spruce (*Picea* sp.) lateral roots, specific gravity (a measure of the weight of the wood or the amount of cell wall material present) increased rapidly between 10 and 50 - 80 cm from the stem and then declined. Riedl found that the maximum values of specific gravity reached were higher than in the stem, but could not explain his findings. This increase in root cell density corresponds with the measurements of compression strength which were higher at 20 - 90 cm along the lateral roots of Norway spruce than in the stem. The compression strength measured by the Fractometer will depend on the specific gravity of the wood, the more dense the wood, the higher the compression strength. Therefore the increase in measured compression strength can be accounted for by changes in specific gravity observed by Riedl and appears to occur at the point of the leeward fulcrum.

In poplar trees of a similar age and size to the Norway spruce examined, the region of highest strength occured much further away from the stem. This increase may be accounted for as a response to stress at the point of maximum bending in "windward" roots, which occurs further from the stem than the leeward hinge (Fig. 4.3). This maximum point would also be at the edge of the root-soil plate, which for trees of this DBH is 1.5 - 2.5 m from the stem (Mattheck & Breloer 1994). An alternative explanation for the increased distance in the region of maximum strength from the stem base, is that due to the wet soil conditions, the older vertical sinker roots had died or were decayed underneath the centre of the tree. The lateral roots would therefore be anchored to the soil at their tips or with younger, healthier sinker roots further away from the tree centre. Forces transmitted from the stem to the soil would therefore have to travel along the length of the lateral root and perhaps to the edges of the soil-root plate, before being dissipated into the ground. The bending action of the crown will therefore place a great strain on the thinner surface roots at the edges of the root-soil plate which may therefore respond with an increase in strength.

Although compression strength did not vary along the lateral roots of Scots pine, the root was much stronger near the stem base as described by the high regression coefficient of root/stem compression strength and distance from the stem. Hintikka (1972), examining pine and spruce of a smilar age and size to those in this study, found that the point of maximum bending in pine roots occurred much nearer the stem than in spruce. He pulled trees horizontally with a winch and measured soil movement in the area of the root-soil plate. He found the maximum soil movement in spruce was 60 - 120 cm from the stem, whereas in pine it was only 20 cm from the stem (Fig. 4.4). The difference in the site of maximum soil movement between the two species is probably due to the anchoring effect of the pine tap root. Positioned in the centre of the root system, the tap root resists movement of the lateral roots by hindering movement of the stem base. Spruce lateral roots moved approximately three times more than pine lateral roots, showing that the big tap root of pine anchors it more firmly than the plate system of spruce. If there is a region of maximum strength in lateral roots of pine, it will occur very close to the stem and cannot be detected with wood samples taken at large intervals along the root.

The lateral roots of Scots pine were the weakest out of all the species examined in the present study. Their role in anchoring the tree is, however very small, as further demonstrated by Hintikka (1972). Hintikka measured the movement of pine tap roots by forcing a solid aluminium rod through the soil so that it touched the tap root at a depth of 25 - 30 cm from ground surface. He found that when the pine stem was pulled only 1° horizontally, the stem and the tap root moved in opposite directions, *i.e.* the tap root moved away from the pull (Fig. 4.5). He concluded that the lateral roots held the stem so rigidly that the thick tap root must move in the opposite direction. From Hintikka's diagrams (Fig. 4.5), it appears that the tap root is firmly attached to the soil at its tip, which may contribute more to the uprooting resistance than the strength of the lateral root attachment. On further investigation of windthrown trees, Hintikka found that two more types of failure were possible: the tree acts as a stake and the tap root is the point of that stake (see Ennos 1993) and the tap root rotates in the soil when the tree is pulled, if it is *not* firmly anchored by the laterals. However, when pines are windthrown, a large mass of soil often moves together with the root system. Hintikka's examination of several thousand fallen pine trees in central Finland suggest that the most common type of root movement involved the whole root system (type 3). Many trees were also found of type 1, where the tap root had made a semi circular movement, but the stem base was still in the original position. Fewer trees indicated movements comparable to that of type 2, where the tap root acts like a stake and rotates about its centre.

Fig. 4.4

Root movements of a pine tree when the stem is inclined horizontally 1°, 2° and 3° (Hintikka 1972)

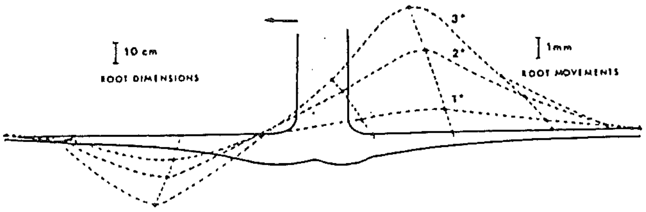
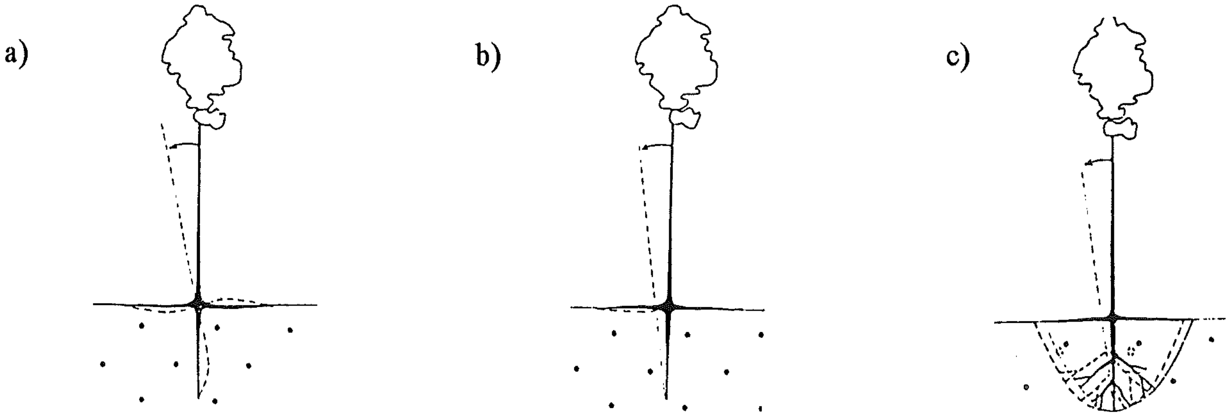


Fig. 4.5

Possible types of root system movement in Scots pine
(from Hintikka 1972)



a) Tap root bending in opposite direction to that of stem and attached at its base and tip.

b) Tap root moving in same direction as the stem with the surface lateral roots moving mainly horizontally.

c) A large mass of soil moving together with the root system when the tree uproots.

The lower sides of lateral roots in plate systems will probably suffer the most compression stress as the roots are pushed onto the bearing surface of the soil below. There will also be an area on the underside which is alternately heavily compressed and tensed as the tree sways in the wind (Fig. 4.2). In lateral roots of poplar species, compression strength was found to increase on the underside. Radial growth is normally inhibited on the underside of roots as this region moves the least in the wind and is often compacted by the weight of the tree pressing it onto the soil. In extreme cases, rays even buckle (Fayle 1968) and specific gravity is affected. Both Riedl (1937) and Seibt (1964) found that rootwood specific gravity decreased with increasing ring width, therefore, where radial growth is inhibited, *i.e.* on the underside of the root, cell density will increase, thereby increasing compression strength.

Trees growing on slopes are subjected to long term static mechanical stress, as opposed to the short term dynamic stress caused by wind forces (Telewski 1994). Roots growing uphill are held in tension and act as ropes, fastening the tree to the ground (Teschner & Mattheck 1994). However, those downslope must act in a way similar to foundation piles of a building, as they are under compressive loading. If the surface area of the root does not increase as a response to the imposed stress, a change in cellular properties may result in a greater strength or stiffness (stiffness is related to the size and material properties of an object). The increase in compression strength found in downslope roots of Norway spruce and at the stem-root base of beech, is possibly due to a higher specific gravity in these regions, although further examination would be required to confirm this hypothesis. However, it appears that permanent mechanical stress may also induce changes within the root system, as well as dynamic loading.

The possible distinction in compression strength found between sinker and lateral roots may also be due to differences in wood anatomy. The more oblique the root, the greater the percentage per unit volume of fibre and ray parenchyma content present (Fayle 1968) (Fig. 4.6). Therefore specific gravity would also be altered. Further work by Fayle (1968) showed that specific gravity measurements taken along the length of an oblique and a vertical root of 130-year-old *Tilia americana*, differed greatly between the two roots, at the same difference from the stem (Fig. 4.7)

Fig. 4.6

Proportion of tissues in an oblique and horizontal root of *Tilia americana* sampled at the same distance from the stem (Fayle 1968)

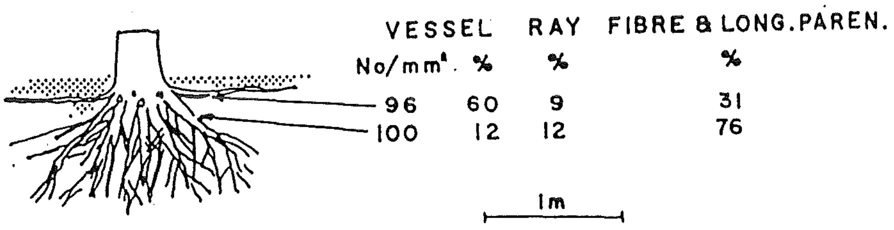
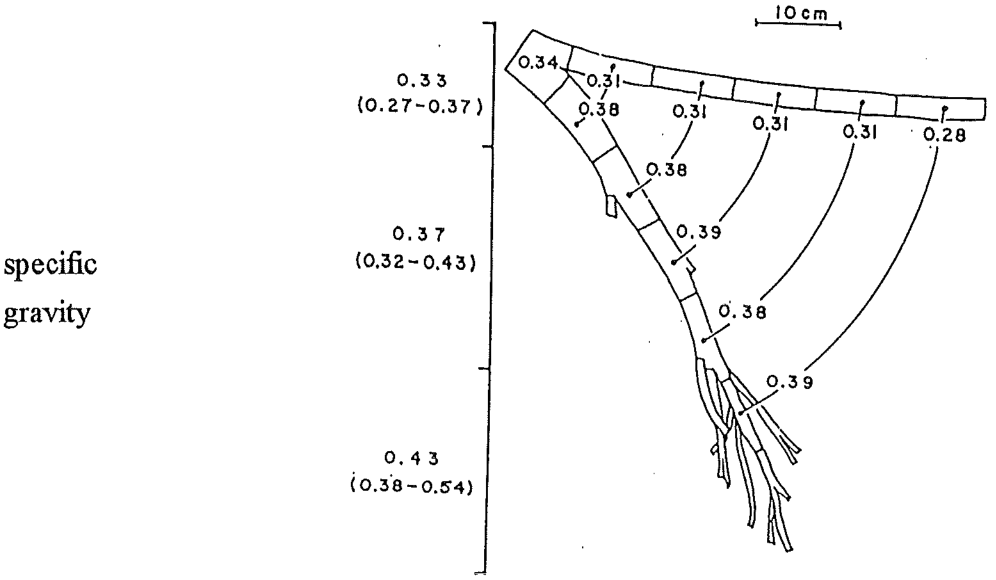


Fig. 4.7

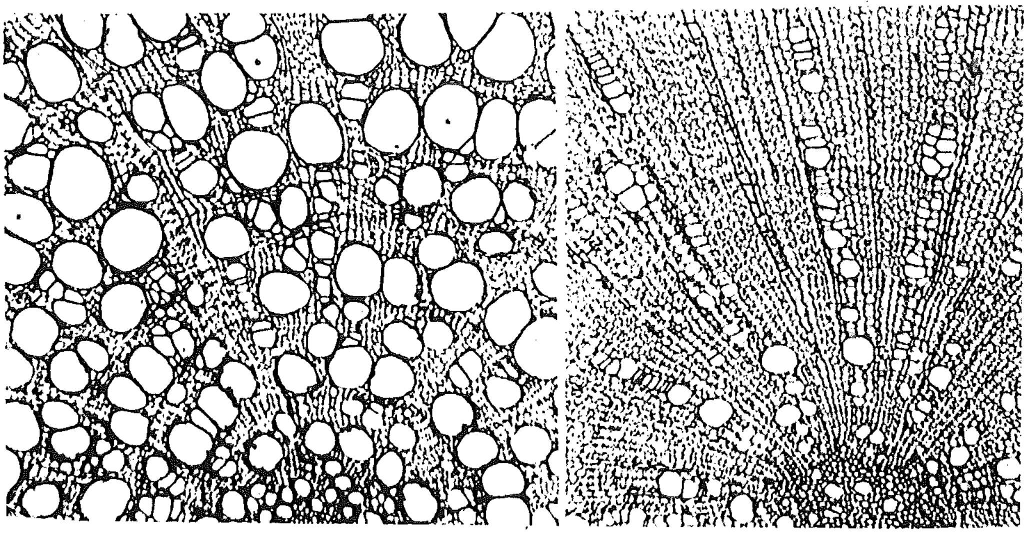
Specific gravity in *Tilia americana* roots is higher in oblique roots compared to horizontal roots, measured at the same distance from the stem (Fayle 1968)



The oblique root of *Tilia americana* had a higher specific gravity and wood anatomy similar to that found in the stem, whereas the horizontal root had a typical lateral root anatomy *i.e.* cell size increased and cell wall thickness became thinner with increasing distance from the stem (Fig. 4.8). Oblique and sinker roots will normally be under a greater compression stress than lateral roots, especially if they are sited underneath the centre of the tree with most of the tree's weight bearing down on them. It appears that fibre content is higher in those areas of the root system which provide the most mechanical support for the tree, namely the root bases and sinker roots.

Fig. 4.8

Cross-sections from the centre of a *Tilia americana* lateral root (left) and an oblique root (right), showing the greater cell density in the more vertical root (from Fayle 1968)



LATERAL ROOT SINKER ROOT

Responses of trees to wind are well-documented but research has centred on effects of wind on the tree stem (see excellent review by Telewski 1994). An important adaptive response of wood to mechanical loading is a change in the stemwood anatomy. The number of tracheids increase and the formation of "flexure" wood (Telewski 1989) occurs under dynamic loading, as opposed to the more familiar "reaction" wood (see Boyd 1977) which occurs when a stem is permanently displaced. Flexure wood is more dense than normal wood, with a smaller tracheid lumen size and microfibrils in the cell wall at a larger angle to the cell axis than normal. Such changes in cell morphology result in a more rigid wood which can better withstand mechanical stress and alters internal compressional strain. As such responses occur in the stem, it is therefore probable that comparable changes can take place in the roots under similar loading, such as the observed increase in specific gravity in regions of maximum bending in the lateral roots of Norway spruce. However, the signal for this mechanism is unknown. Larson (1965) suggested that resources are diverted from stem height to diameter growth under the influence of mechanical stress and auxin levels. Ethylene production is known to increase under mechanical stress and is thought to be the mediator of increased cell radial growth and reduced elongation. Possibly, ethylene was produced in stressed areas of the roots, and induced changes in rootwood anatomy which in turn affected the strength values. It is likely that the mechanically stressed areas receive more resources, but probably at the expense of another part of the plant.

There is very little literature regarding the existence of different types of root systems in mature trees. Young trees normally have a tap root and many horizontal roots, but as the tree matures, the tap root does not develop further and plays a smaller role in the support of the tree. Ennos (1993) attributes this to the expense of resources required in developing the tap root. As trees get larger, the efficiency of tap root systems will not increase but that of plate systems will. The anchorage provided by the weight of the root-soil plate rises with the fourth power of linear dimensions rather than with their cube, therefore plate systems should be favoured by trees. Ennos however, does not acknowledge the cost of constructing heart systems, though presumably he classifies them together with plate systems. There appears to be a greater number of European tree species with heart rather than plate or tap systems in maturity (Table 4.2) (Köstler *et al.* 1968).

Table 4.2

Some species with different types of root systems found in Europe

Type of tree	Plate	Heart	Tap
ANGIOSPERM:	*Fraxinus excelsior*	*Acer pseudoplatanus*	*(Quercus sp.)*
	Populus tremula	*Acer campestre*	*(Robinia pseudoacacia)*
	(Populus sp.)	*Acer platanoides*	
	Robinia pseudoacacia	*Alnus glutinosa*	
	Sorbus aucuparia	*Alnus incana*	
		Betula verrucosa	
		Carpinus betulus	
		Castanea sativa	
		Fagus sylvatica	
		(Populus sp.)	
		Prunus avium	
		Quercus robur	
		Quercus petraea	
		Quercus rubra	
		Tilia cordata	
		Tilia platyphyllos	
		Ulmus montana	
		Ulmus glabra	
		Ulmus effusa	
GYMNOSPERM:	*Picea abies*	*Larix decidua*	*Abies alba*
	Picea sitchensis	*Larix leptolepis*	*Pinus sylvestris*
	Pinus strobus	*Pseudotsuga taxifolia*	*Pinus nigra*
			Pinus contorta

(Species in brackets can commonly be found with that type of root system, depending on local conditions).

Further information can be found in Büsgen 1929, Köstler *et al.* 1968, Sutton 1969 and Eis 1978.

It is significant that tap root systems hardly ever occur in soft- or hardwoods. Shallow rooting plate systems are also found in only a few hardwoods *e.g.* ash and poplar, the latter often becoming a heart system when soil conditions are favourable. A tree will uproot if bending forces on the stem exceed the root-soil strength, but are not strong enough to break the stem. Therefore tree species with shallow rooting systems will be more likely to overturn by the wind compared to deeper rooted tree species, even though the vertical sinker roots act as a series of reiterated tap roots (Gruber 1994). Small increases in rooting depth result in a much greater resistance to uprooting (Fraser 1962). Yet spruce, with its plate system is one of the commonest trees found in wind exposed places such as the tree line of mountains. One reason for the development of such a shallow system is that, as Ennos (1993) suggests, it is much cheaper to construct this type of system than to build a large tap root. More resources can then be used for *e.g.* needle growth and maintenance. However, this reason alone does not explain the development of such seemingly poor anchoring systems. In a study of the mode of failure of tropical hardwoods and wood quality, Putz *et al.* (1983) suggested that larger trees with dense, strong wood were more prone to uprooting than stem snapping. The mass of large, heavy trees under dynamic stress increases the strain on the root-soil interface and hence the likelihood of exceeding soil shear strength. However, smaller trees generally have relatively larger root systems and so will be more firmly anchored, thus increasing the possibility of stem breakge. It appears that snapped trees which are capable of resprouting from the stem, have larger root systems and also a positional advantage over smaller trees, hence occupying openings in the canopy resulting from tree fall (Smith 1972). If a tree is healthy, resprouting from the tops of broken stems may therefore compensate for stem failure, and allow the tree to maintain its position in the canopy (Putz *et al.* 1983). Gymnosperms are unable to produce fast growing sprouts from a broken stem, therefore whichever type of failure occurs will probably be fatal. As resprouting is one way in which an angiosperm can survive after mechanical failure, a relatively large investment in the root system will help prevent uprooting. Coniferous species however, do not need to invest as much into constructing a well anchored root system, as both stem and root failure will be likely to result in the death of the tree. A redistribution of resources to the most mechanically stressed parts of the root system will be the most economic way for conifers to compensate for a lack of stability, especially in shallow plate systems.

The strength of lateral roots appears to be influenced by intrinsically different root system types. In heart and tap root systems, strength along a root decreases more rapidly than in plate root systems. A fundamental aspect of root anchorage is the transfer of external loading forces into the ground. In highly branched systems, or in the presence of a tap root, this occurs close to the stem. In plate root systems, where the rate of branching is less, forces must be transferred down sinker roots or along the length of the lateral root. Resources appear to have been distributed to those areas in roots under the most mechanical stress, causing regions of maximum strength. If such responses to external loading can be identified, they may be manipulated for use in future breeding programs, or the management of forest crops may be altered to induce an increase in tree stability.

Acknowledgements

I would like to thank Professor Claus Mattheck for his help over the last year, especially for patiently explaining the basics of tree biomechanics to me many times! Without his expertise in this field, a further understanding of root system mechanics would remain unearthed.

Many thanks are due to all those who helped with the fieldwork and problem-solving over the last year, especially to Jürgen Hämmerle. Jürgen kindly drove me to my field-site many times and also translated the report abstract into German for me.

Thanks are also due to the Forschungszentrum Karlsruhe for inviting me to work here and funding the project.

References

Albrecht W.A., Bethge K. & Mattheck C. 1995, Is lateral strength in trees controlled by lateral mechanical stress? J. of Arboriculture - in press.

Bannan M.W. 1937, Observations on the distribution of xylem-ray tissue in conifers. Ann. of Bot. 1,4: 717-726.

Boatwright S.W.J. & Garrett G.G. 1983, The effect of microstructure and stress state on the fracture behaviour of wood. J. of Materials Science 18: 2181-2199.

Boyd J.D. 1977, Basic cause of differentiation of tension wood and compression wood. Aust. For. Res. 7: 121-143.

Burdett A.N. 1978, Juvenile instability in planted pines. Irish Forestry 36: 36-47.

Büsgen M., Munch E. & Thomson T. 1929, The structure and Life of Forest Trees. Chapman and Hall, London.

Coutts M.P. 1983, Root architecture and tree stability. Plant and Soil 71:171-188.

Coutts M.P. 1986, Components of tree stability in Sitka spruce on peaty gley soil. Forestry 59: 173-197.

Coutts M.P. 1987, Developmental processes in tree root systems. Can. J. For. Res. 17:761.767.

DeSmidt W.J. Studies of the distribution and volume of the wood rays in slippery elm (*Ulmus fulva* michx.). J. of Forestry 20: 352-362.

Easterling K.E., Harrysson R., Gibson L.J. & Ashby M.F. 1982, On the mechanics of balsa and other woods. Proc. R. Soc. Lond. A 383: 31-41.

Ennos A.R. 1990, The anchorage of leek seedlings: the effect of root length and soil. Ann. of Bot. 65: 409-416.

Ennos A.R. 1993, The scaling of root anchorage. J. Theor. Biol. 161: 61-75.

Ennos A.R. 1994, The biomechanics of root anchorage. Biomimetics 2: 129-137.

Ennos A.R. & Fitter A.H. 1992, Comparative functional morphology of the anchorage systems of annual dicots. Funct. Ecol. 6: 71-78.

Ennos A.R., Crook M.J. & Grimshaw C. 1993, A comparative study of the anchorage systems of Himalayan balsam *Impatiens glandulifera* and mature sunflower *Helianthus annuus*. J. of Exp. Bot. 44: 133-146.

Eis S. 1978, Natural root forms of western conifers. Symposium on Root Form of Planted Trees, Victoria, B.C., Canada. pp. 23-27.

Fayle D.C.F. 1968, Radial growth in tree roots. Technical Report No. 9. Faculty of Forestry, University of Toronto.

Fayle D.C.F. 1976, Stem sway affects ring width and compression wood formation in exposed root bases. Forest Sci. 22: 193-194.

Fraser A.I. 1962, The roots and soil as factors in tree stability. Forestry 35: 117-127.

Fraser A.I. & Gardiner J.B.A. 1968, Rooting and stability in Sitka spruce. Forestry Commission Bulletin 40. HMSO.

Gray D.H. 1978, Role of woody vegetation in reinforcing soils and stabilizing slopes. In: Soil Reinforcing and Stabilizing Techniques, Oct. 1978, The New South Wales Inst. of Technology, Sydney, Australia.

Grayson A.J. 1989, The 1987 storm: impacts and responses. Forestry Commission Bulletin 87. HMSO.

Gruber F. 1994, Morphology of coniferous trees: possible effects of soil acidifcation on the morphology of Norway spruce and Silver fir. In: Effects of Acid Rain on Forest Processes. Edited by A Hütterman, D. Godbold. Wiley-Liss Inc., pp. 265-324.

Hale J.D. & Clermont L.P. 1963, Influence of prosenchyma cell-wall morphology on basic physical and chemical characteristics of wood. J. of Polymer Sci. 2: 253-261.

Harlow W.M. 1927, The effect of site on the structure and growth of White cedar *Thuya occidentalis* L. Ecology 8:453-470.

Hathaway R.L. & Penny D. 1975, Root strength in some *Populus* and *Salix* clones. N.Z.J. Bot. 13, 333-344.

Hintikka V. 1972, Wind-induced movements in forest trees. Metsäntutkimuslitoksen Julkaisuja 76: 1-56.

Jacobs M.R. 1954, The effect of wind sway on the form and development of *Pinus radiata* D. Don. Aust. J. Bot. 2: 35-51.

Kellogg R.M. & Ifju G. 1962, Influence of specific gravity and certain other factors on the tensile properties of wood. Forest Products Journal. Vol. 12: 463-468.

Köstler J.N., Brückner E. & Bibelriether H. 1968, Die Wurzeln der Waldbäume. Verlag Paul Parey, Hamburg & Berlin.

Kramer P.J. & Kozlowski T.T. 1979, Physiology of Woody Plants. Academic Press.

Larson P.R. 1965, Stem form of young *Larix* as influenced by wind and pruning. Forest Sci. 11: 412-424.

Lebedenko L.A. 1962, Comparative anatomical analysis of the mature wood of roots and stems of some woody plants. Trud. Inst. Les. Akad. Nauk. SSSR (Sib. Otdel) 51: 124-34. (See Fayle 1968 for translation).

Mattheck C. 1991, Trees: the Mechanical Design. Springer-Verlag.

Mattheck. C. 1993, Design in der Natur: Der Baum als Lehrmeister. Rombach Verlag.

Mattheck C. & Breloer H. 1992, Der wurzelquerschnitt als protokoll der lastgeschichte. (Root cross-sections tell the load history). All. Forst-u. J.-Ztg. 163: 142-145.

Mattheck C. & Breloer H. 1993, Handbuch der Schadenskunde von Baümen - der Baumbruch in Mechanik und Rechtsprechung. Rombach-Verlag, Freiburg.

Mattheck C. & Breloer H. 1994, Field guide for visual tree assessment (VTA). Arboricultural Journal 18: 1-23.

Mattheck C., Albrecht W., Dietrich F. & Kriechbaum R. 1994, Die Biomechanik der Holzstrahlen. (The biomechanics of rays in trees). Allg. Forst- u. J.-Ztg. 165: 143-147.

Mattheck C., Bethge K. & Zipse A. 1994, Das Fractometer. Allgemeine Forst Zeitschrift 14:790-791.

Myer J.E. 1922, Ray volumes of the commercial woods of the United States and their significance. J. of Forestry 20: 337-351.

Nicoll B.C., Easton E.P., Milner A.D., Walker C. & Coutts M.P. 1995, Wind stability factors in tree selection: distribution of biomass within root systems of Sitka spruce clones. In: Wind and Trees (Eds. J. Grace & M.P. Coutts) In press.

Niklas K.J. 1992, Plant Biomechanics. An Engineering Approach to Plant Form and Function. The University of Chicago Press.

Putz F.E., Coley P.D., Lu K., Montalvo A. & Aiello A. 1983, Uprooting and snapping of trees: structural determinants and ecological consequences. Can. J. of For. Res.13: 1011-1020.

Riedl H. 1937, Bau und Leistungen des Wurzelholzes. Jahrbücher für Wissenschaftliche Botanik. Verlag von Gebrüder Borntrãger, Leipzig. pp. 1-75.

Schweingruber F.H. 1990, Anatomie Europäischer Hölzer - Anatomy of European Woods. Eidgenössiche Forschungsanstalt für Wald, Schnee und Landschaft, Birmensdorf (Hrsg.) Haupt, Bern und Stuttgart.

Seibt G. 1964, Über die unterschiedliche Raumdichte und Jahrringbreite des Wurzelholzes von Nadelbäumen in einem Meliorationsversuch. Allg. Forst.-u J.-Ztg. 135: 66-74.

Sharon E.M. 1973, Some histological features of *Acer saccharum* wood formed after wounding. Can. J. For. Res. 3: 83-89.

Shigo A.L. 1972, Ring and ray shakes associated with wounds in trees. Holzforschung 26: 60-62.

Smith A.P. 1972, Buttressing of tropical trees: a descriptive model and new hypotheses. Am. Nat. 106: 32-46.

Southon T.E., Mattson A. & Jones R.A. 1992, NMR imaging of roots: effects after root freezing of containerised conifer seedlings. Physiol. Plant. 86: 329-334.

Stokes A. 1994, Responses of young tress to wind: effects on root architecture and anchorage strength. PhD Thesis, University of York, U.K.

Stokes A., Fitter A.H. & Coutts M.P. 1995a, Responses of young trees to wind: effects on root growth. In: Trees and Wind. (Eds. J. Grace & M.P. Coutts). In press.

Stokes A. Fitter A.H. & Coutts M.P. 1995b, Responses of young trees to wind and shading: effects on root architecture. Submitted to J. of Exp. Bot.

Stokes A., Ball J., Fitter A.H. & Coutts M.P. 1995c, Tree root architecture and anchorage efficiency. Submitted to Ann. of Bot.

Sutton R.F. 1969, Form and Development of Conifer Root Systems. Commonw. Agric. Bur. Tech. Commun. No. 7.

Telewski F.W. 1989, Structure and function of flexure wood in *Abies fraseri.* Tree Physiology 5, 113-122.

Telewski F.W. 1995, Wind induced physiological and developmental responses in trees. In: Wind and Trees. (Eds. J. Grace & M.P. Coutts). In press.

Teschner M. & Mattheck C. 1994, A new optimization method for soil anchorages. PD-Vol. 64-8.3, Engineering Systems and Design Analysis. Vol. 8: Part C. pp 741-746.

Waldron L.J. 1977, The shear resistance of root-permeated homogenous and stratified soil. Soil Sci. Soc. Am. J. 41: 843-849.

Waldron L.J. & Dakessian S. 1981, Soil reinforcement by roots: calculations of increased soil shear resistance from root properties. Soil Sci. 132: 427-435.

Wilson B.F. 1964, Structure and growth of woody roots of *Acer rubrum* L. Harv. For. Pap. No. 11.

Wilson B.F. 1975, Distribution of secondary thickening in tree root systems. In: The Development and Function of Roots. (Eds. J.G. Torrey & D.T. Clarkson). Academic Press, New York. pp. 197-219.

Wu T.H. 1976, Investigation of landslides on Prince of Wales Island, Alaska. Geotechnical Report No. 5, Department of Civil Engineering, Ohio State University

Appendix A
Instructions to Predict Tree Root Strength

1. Measure the diameter of the tree at breast height. Convert this value into cross-sectional area (CSA):

diameter/2 = radius

3.14 (radius x radius) = CSA

2. Take a core sample from the tree at breast height and measure the compression and lateral bending strength at 12 mm intervals. Calculate the average value for both strengths.

3. Take a core sample from the lateral root. Note distance from stem.

4. Measure the width and height of the lateral root where core was taken. (Height is the increment core length, if the core went through the entire root. If not, some digging is required to estimate root height)!

5. Calculate CSA for the section of root where the core sample was taken from. If the root is close to the stem, oval shaped buttress roots often develop. If root height is more than twice the diameter, treat the section as a rectangle: simply multiply height with diameter. If the root is more circular, take the average value of height and diameter and calculate CSA, as for the stem above.

6. Divide root CSA by stem CSA.

7. Divide root strength by average stem strength (this can be done for individual increments of the core, or for the average strength of the core)

TO USE GRAPH

8. On the X axis, find the distance class from the stem to which your root value belongs e.g. a sample 40 cm from the stem lies in the distance class: 35 - 44 cm.

9. On the left Y axis, find where your CSA value lies, then move finger along to the distance class. If the value lies in the shaded box above the distance class, then you should be able to predict root strength values confidently. If the value lies above or below the box, take care when predicting root strength.

10. Finally, find where your strength value lies on the right Y axis. Move finger along to the distance class. If the lateral bending strength values lie in the dark grey range (or above it) and the compression strength values lie in the light grey range (or above it), all should be well. If the values lie below these ranges, take a closer look at the root.

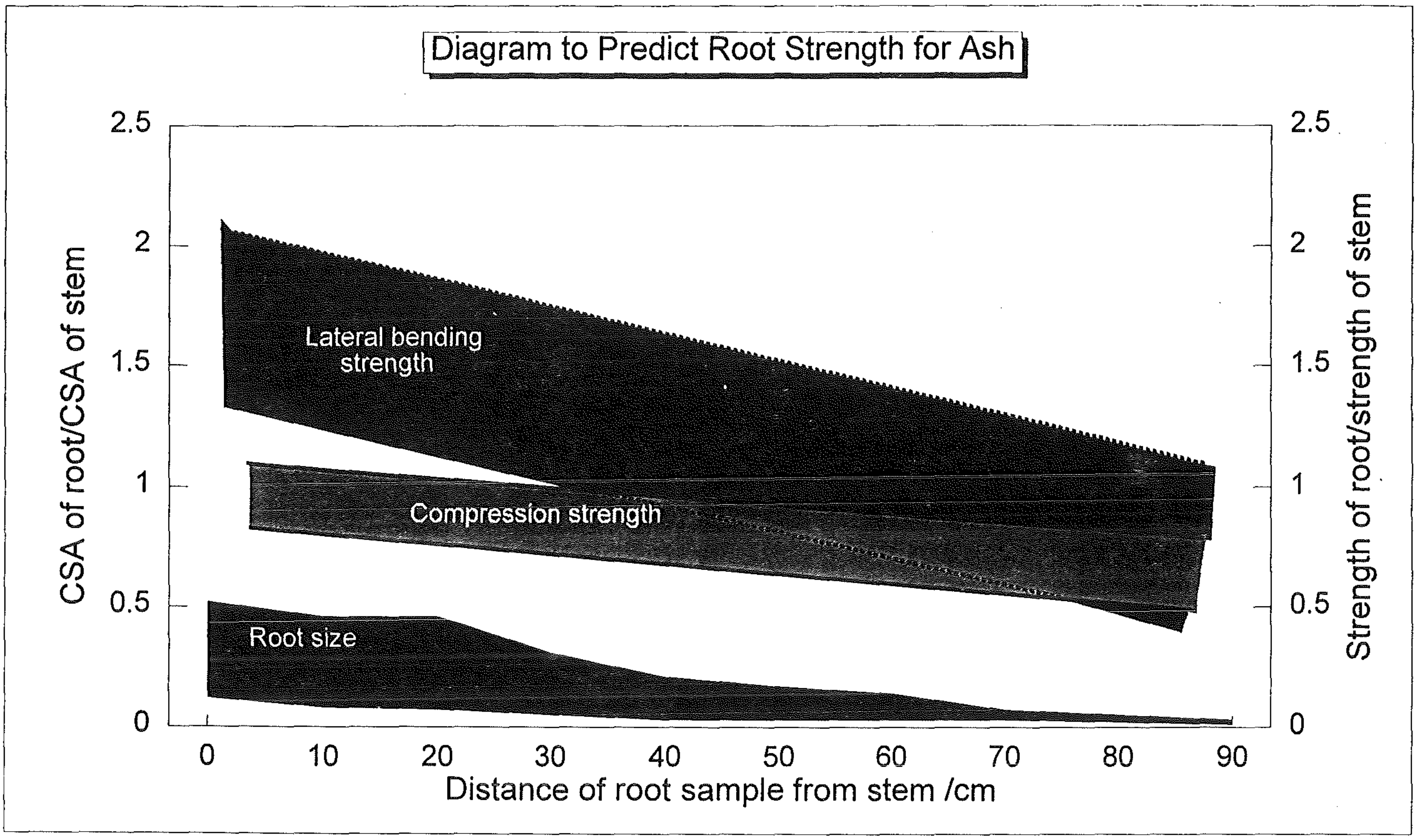


Diagram to Predict Root Strength for Ash

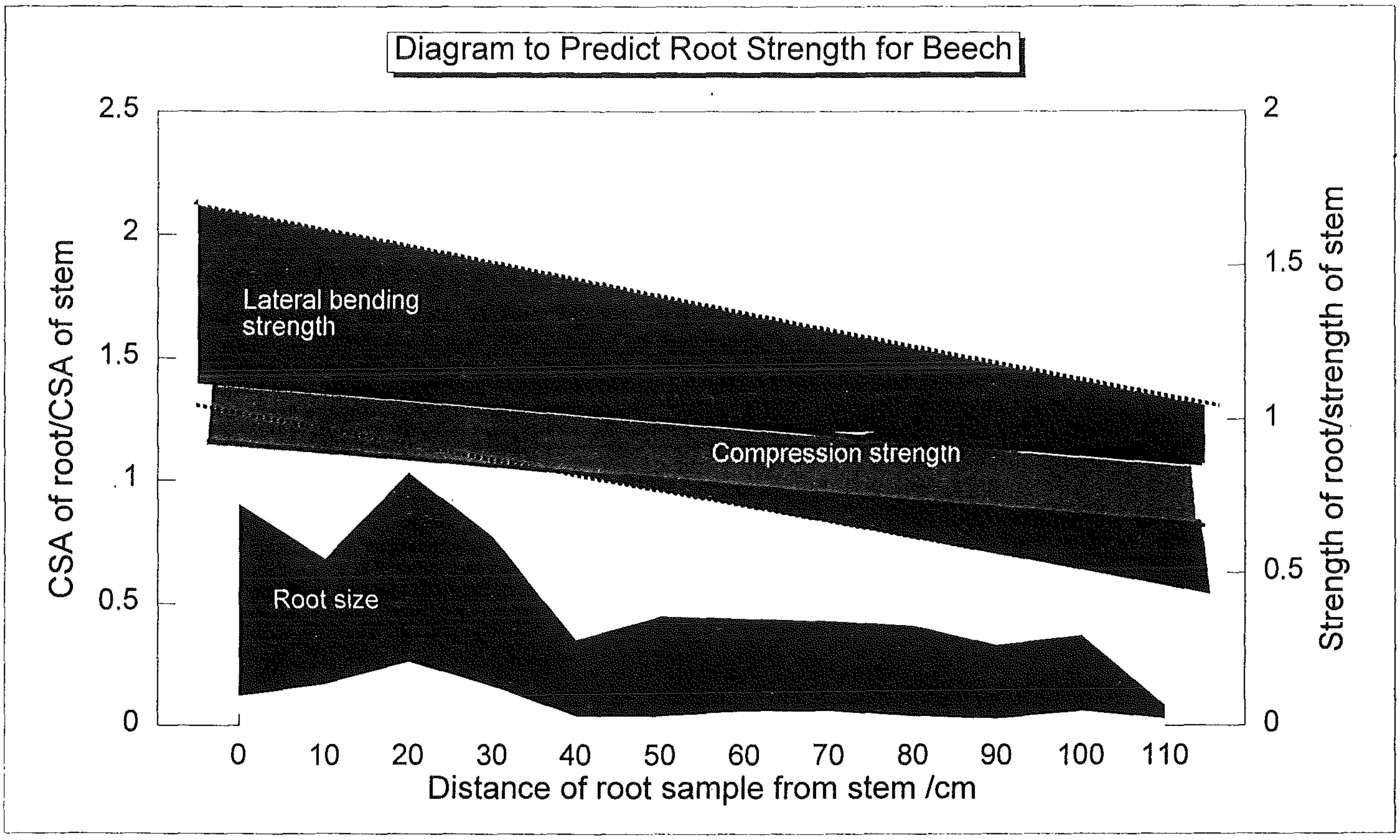


Diagram to Predict Root Strength for Beech

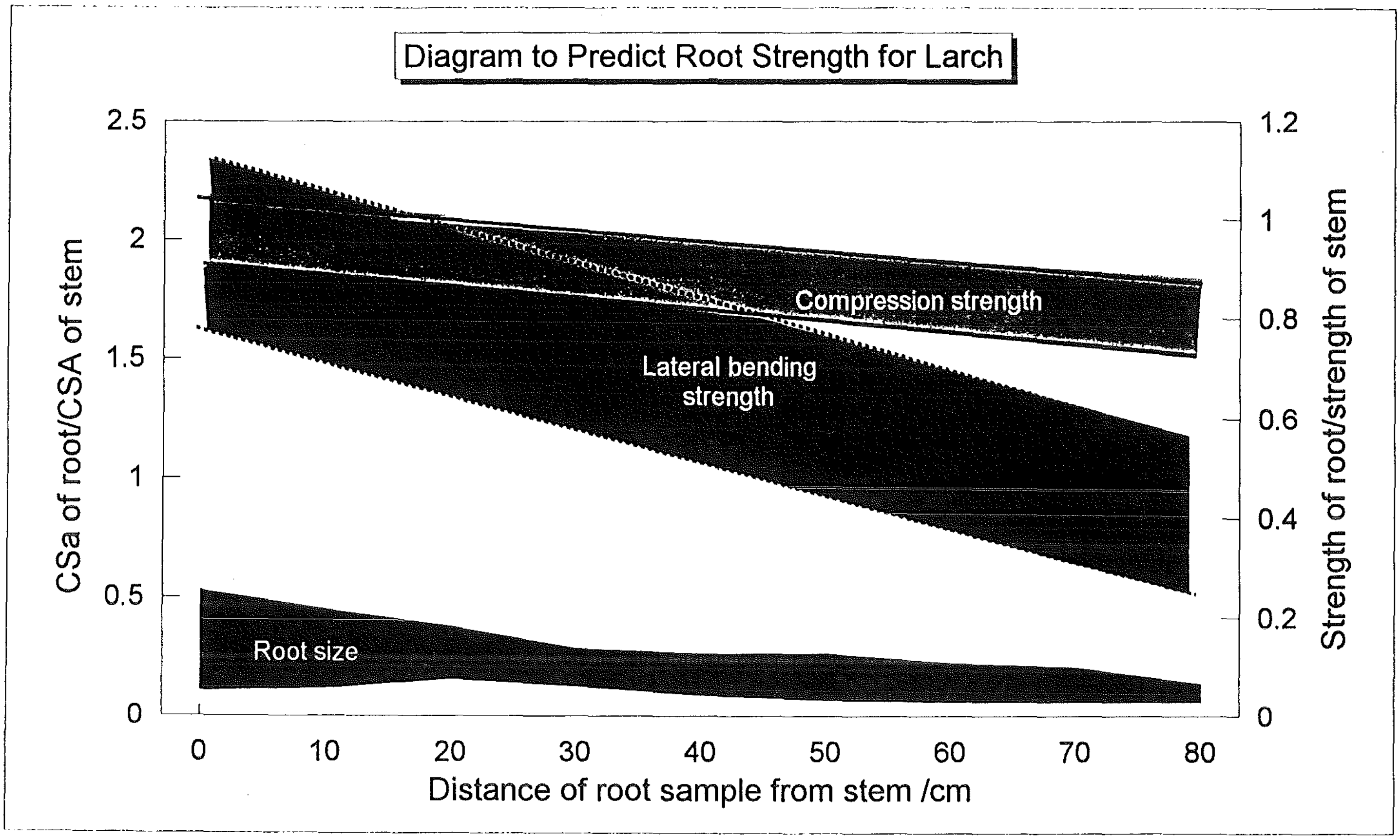


Diagram to Predict Root Strength for Larch
2.5
2
1.5
1
0.5
0
CSa of root/CSA of stem
1.2
1
0.8
0.6
0.4
0.2
0
Strength of root/strength of stem
Compression strength
Lateral bending strength
Root size
0
10
20
30
40
50
60
70
80
Distance of root sample from stem /cm

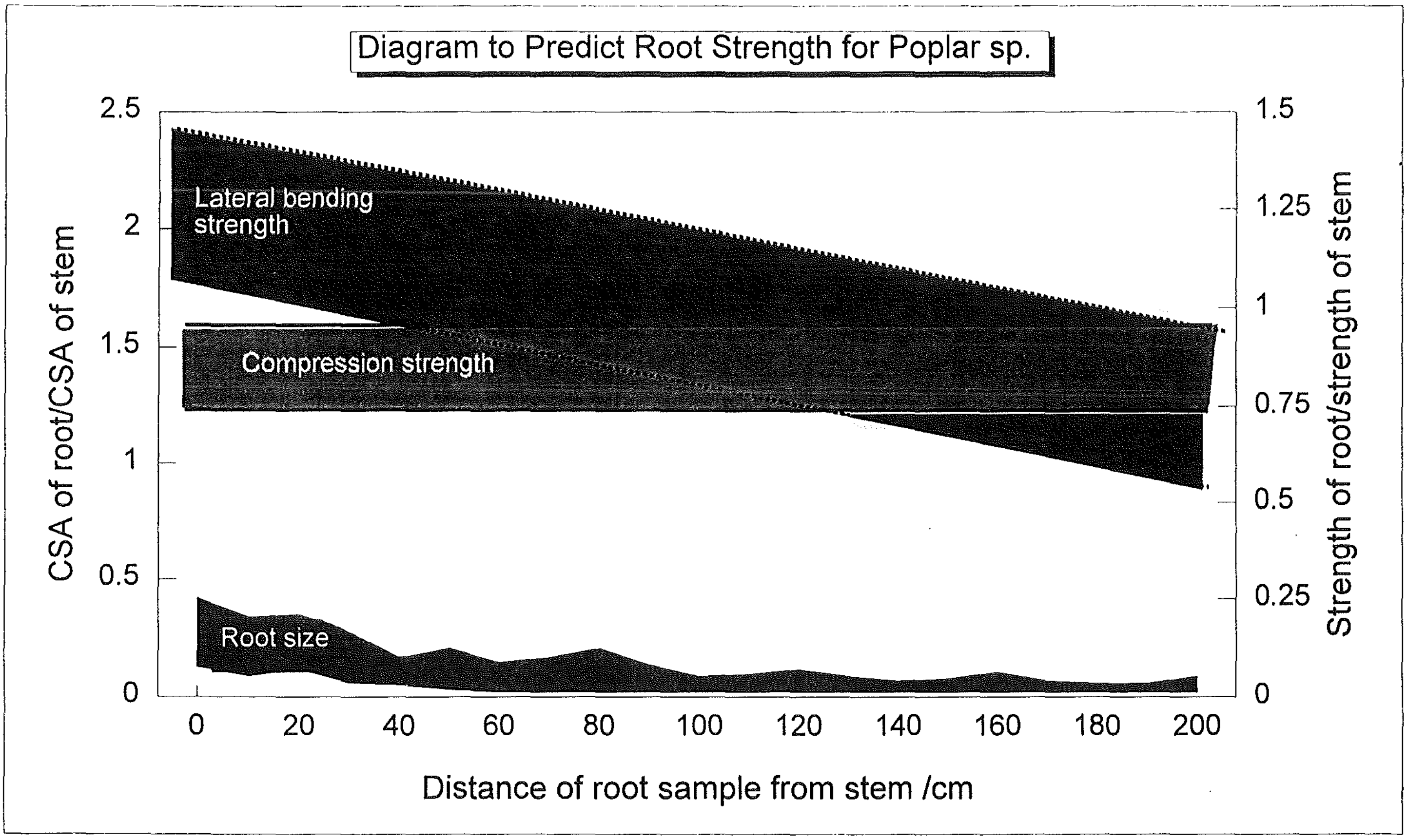


Diagram to Predict Root Strength for Poplar sp.
2.5
2
1.5
1
0.5
0
CSA of root/CSA of stem
1.5
1.25
1
0.75
0.5
0.25
0
Strength of root/strength of stem
Lateral bending strength
Compression strength
Root size
0
20
40
60
80
100
120
140
160
180
200
Distance of root sample from stem /cm

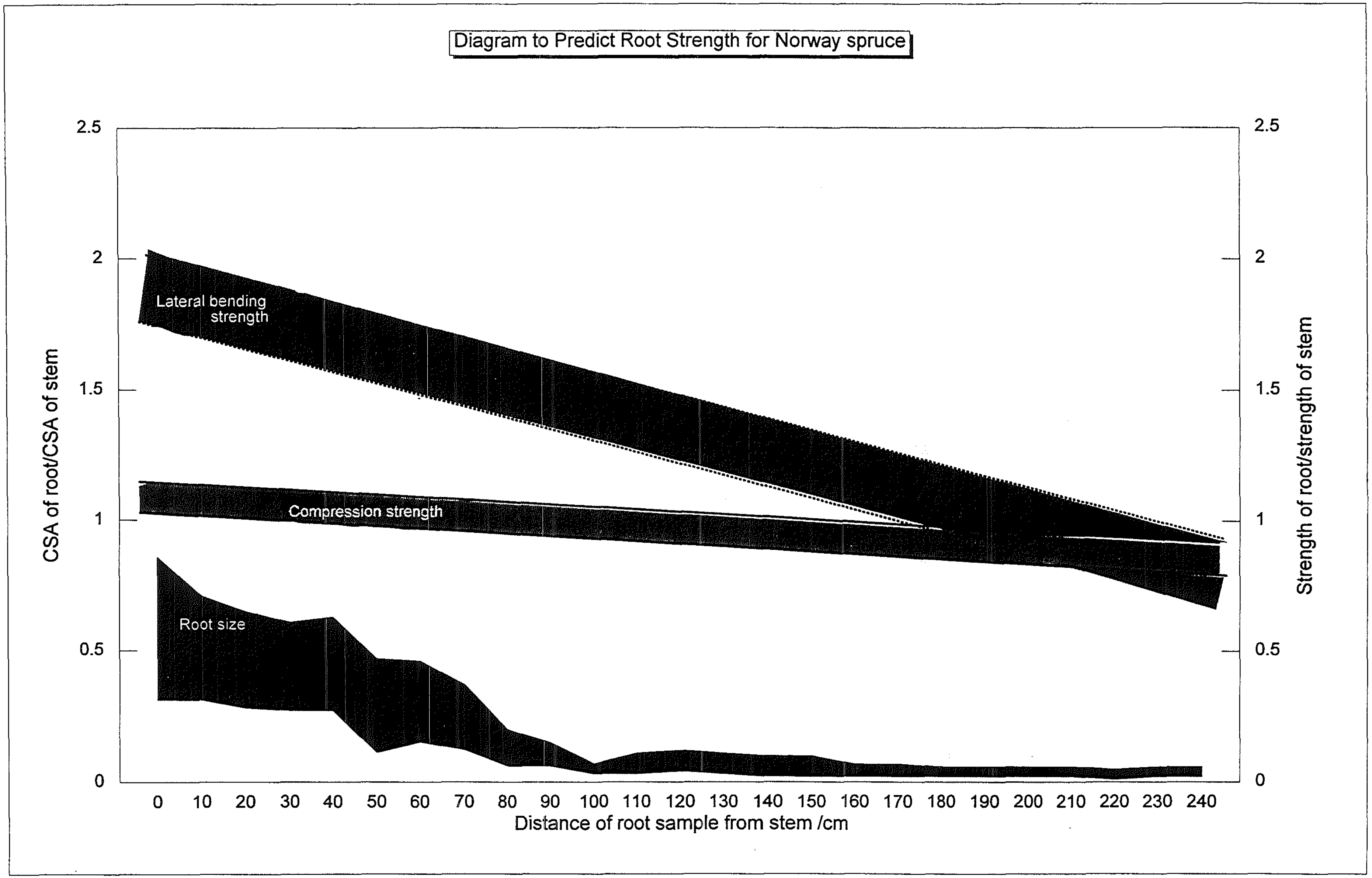


Diagram to Predict Root Strength for Norway spruce
CSA of root/CSA of stem
Strength of root/strength of stem
2.5
2
1.5
1
0.5
0
Lateral bending strength
Compression strength
Root size
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240
Distance of root sample from stem /cm

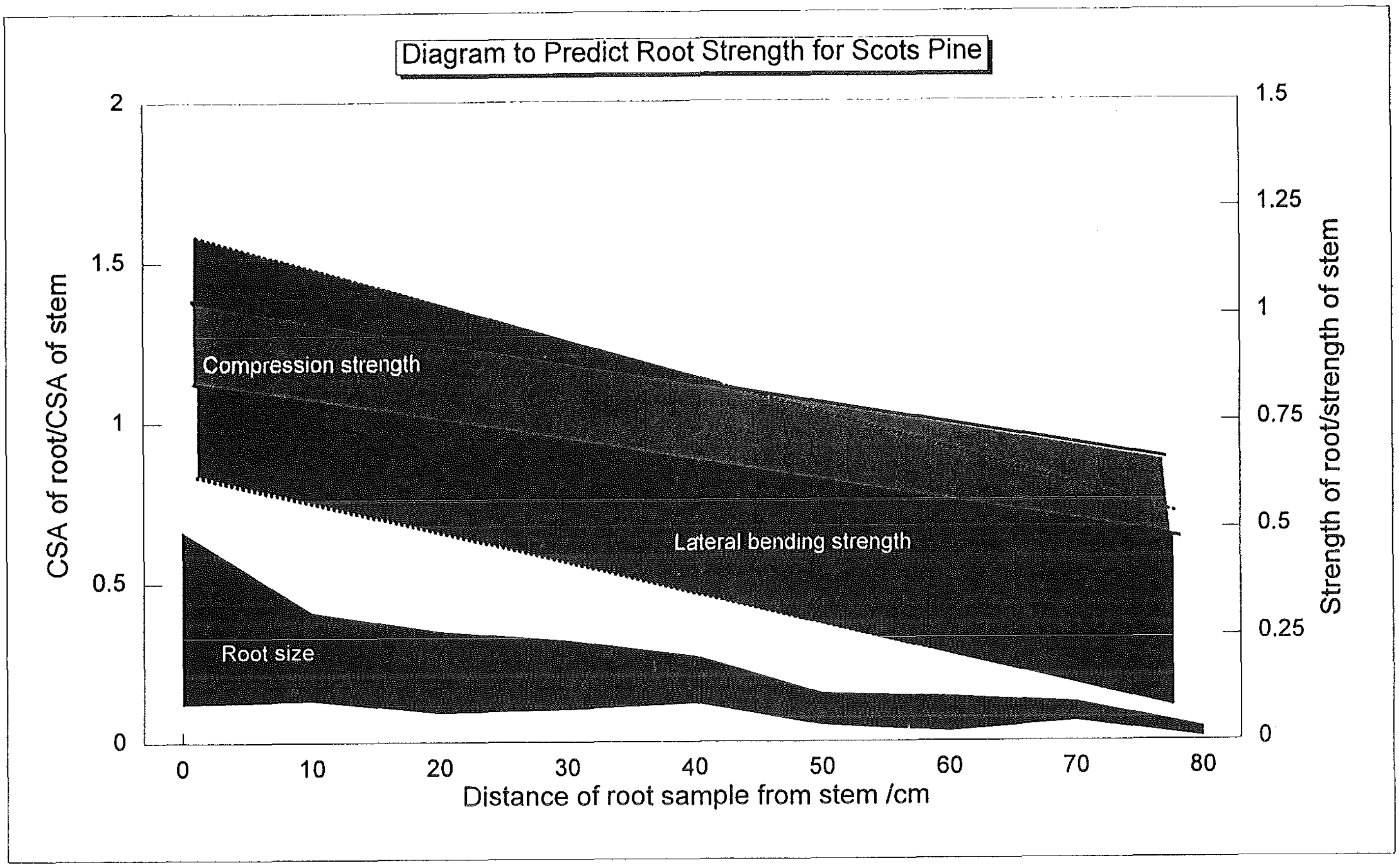


Diagram to Predict Root Strength for Scots Pine

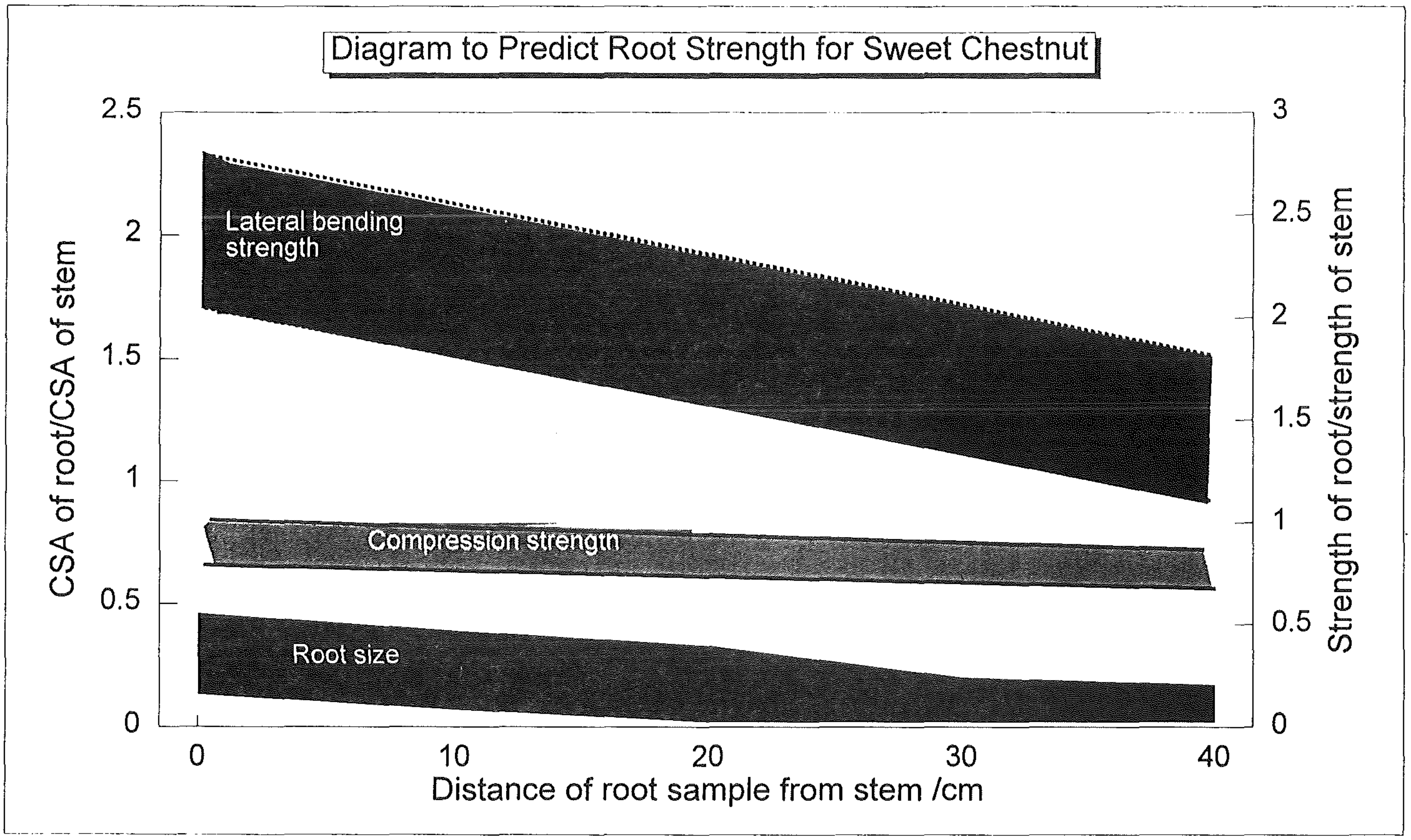


Diagram to Predict Root Strength for Sweet Chestnut