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**GESTION DES RISQUES RELATIFS A LA STABILITE DES ARBRES PAYSAGERS: BIOMECANIQUE ET ARCHITECTURE DU SYSTEME RACINAIRE**

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Abstract

The studies presented in this thesis is primarily concerned with the biomechanics and root system architecture of temperate and tropical trees, grown on different environments with intrinsically different root architectural patterns. Together with root morphology analysis, the best predictors were determined and correlated to tree anchorage and stability.

The effect of root cutting through trenching on the anchorage of mature *E. grandis* grown on urban landscape in Kuala Lumpur, Malaysia was studied by combining tree winching and trenching tests where the influence of root loss were quantified. Critical turning moment ($TM_{crit}$) and tree anchorage rotational stiffness (TARS) before and after trenching were calculated. Root systems architectural analysed and relationships between architectural parameters and $TM_{crit}$ and TARS were investigated. No differences were found between $TM_{crit}$ and trenching distance. In control trees, significant relationships only exist between both $TM_{crit}$ and both single and combinations of parameters e.g. rooting depth, no of laterals and root plate size. TARS was significantly decreased when roots were cut at 0.5 m only. Surprisingly, no relationships existed between $TM_{crit}$ and TARS with any root system parameter when trenching was carried out at 1.0 m. The results showed that in terms of TARS and $TM_{crit}$, mechanical stability was not significantly affected by trenching on sandy clay soil, due to rooting depth of the sinkers which occurred close to the trunk and root plate size which provide greater stiffness thus play a major component of anchorage in *E. grandis*.

The effect of root cutting through trenching was also investigated on deep-rooted mature *Pinus pinaster* Ait grown on sandy podzol soil, in the south-west of France. No differences were found between $TM_{crit}$ with trenching distance. However, significant difference was found between TARS and trenching distances and TARS was significantly decreased when roots were cut at 0.5 and 1.0 m from the trunk. In trees where roots were cut at 0.5 and 1.0 m, significant relationships were found between $TM_{crit}$ and combinations of parameters e.g. root CSA, DBH, tree height and relative root depth. When roots were cut at 1.5 m from trunk, TARS was found significant with both, single and combination of parameters such as root CSA, stem dimensions, no of sinker roots, total and relative root depth. Our study showed that in terms of TARS and $TM_{crit}$, mechanical stability was not greatly affected by trenching, probably because most of the root biomass can be found close to the trunk at distance of less than 0.5 m and therefore contribute to a significant component on anchorage in mature *P. pinaster* tree.

In order to determine the most important characters governing mechanical resistance to rockfall and wind loading, static winching tests were carried out on three tree species: Silver fir (*Abies alba* Mill.*)*, European beech *(Fagus sylvatica* L.*)* and Norway spruce *(Picea abies* L.) in a mixed forest stand. Trees were winched to an angle of 0.25° at the stem base, both up- and downhill and finally to failure. Strain gauges were attached to the stem and one up- and downhill lateral root in order to determine the distribution of strain within the tree during overturning and root morphology measured for all uprooted tree. No significant differences were found in the force necessary to winch trees up- and downhill between species. Strain was significantly higher in lateral roots of Silver fir than in roots of Norway spruce and European beech when winched downhill. Downhill roots of Norway spruce were largely held in tension when trees were pulled downhill, whereas in Silver fir and European beech, they were held in compression. In uphill pulled, strain decreased along the lateral root of downhill roots only. European beech possessed a significantly greater number of second order lateral roots than either Norway spruce or Silver fir. Norway spruce possessed a higher proportion of total root length near the soil surface, whereas European beech had the greatest proportion in the intermediate depth class and Silver fir had the highest maximal root depth. Norway spruce had a significantly lower proportion of oblique roots than the other two species, resulting in a plate-like root system which was less resistant to overturning than Silver fir or European beech.

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Finally, I dedicated this thesis to my wife, Nur Haslina Mukhtar. This research could not have been accomplished without the sacrifice, understanding, patience, love and unconditional support.

**List of symbols**

| | | |
|---|---|---|
| CSA | - | cross sectional area ($mm^2$). |
| DBH | - | diameter at breast height (m). |
| DSB | - | diameter at stem base (cm). |
| *e* | - | root eccentricity. |
| RARS | - | relative tree anchorage rotational stiffness (%). |
| TARS | - | tree anchorage rotational stiffness (kNm/rad). |
| TM | - | overturning moment (kNm). |
| $TM_{crit}$ | - | critical turning moment (kNm). |

# CHAPTER 1: INTRODUCTION

Background

This thesis provides various studies carried out on the anchorage mechanisms of different landscape species found in different environment (tropical and temperate). Their mechanical role in terms of providing stability and anchorage were discussed with the aim of providing guidelines and advice to the management dealing with managing potential hazardous trees in landscape areas.

The presence of trees has always been claimed to provide benefits and values to the community and surrounding environments. In urban areas, their main functional use is to beautify the landscape area and provide shade for human activities, meanwhile in hilly and mountainous areas, they provide protection against natural hazards such as landslide, rockfall and avalanches (Brang 2001, Dorren et al 2004, Dorren and Berger 2006, Hurand and Berger 2002, Motta and Haudemand 2000, Ott 1996). With the increase in the intensity and frequency of catastrophic natural disasters such as high storms, avalanches and rockfall due to the increase in extreme weather events (Sauri et al 2003, Maracchi et al. 2005, Tianchi et al. 2002) around the world and recognizing their impact on the safety of the people and properties, ecology and economic value, more research has been focused into this area. In France, the 1999 hurricane was the most violent storm, resulted in 15 million hectares of wind-blown trees (Stokes 2000) and also an estimated losses of 26.1 million $m^3$ of wood or equivalent to 3.5 years of harvest (Cucchi and Bert 2004). Damage is not only limited to forest trees, where many urban trees were also damaged. Quine (1991) estimated the volume of damaged trees caused by 1987 and 1990 wind storms in Britain was 85,000 $m^3$ which involve 170,000 trees. However, these figures do not include the disruption to infrastructure or structural damage to buildings, as well as injuries and fatalities to human. Furthermore, as most of a tree's structural roots are found near the soil surface, trees in urban landscape are also subjected to severe environmental stresses and mechanical damage, especially to root systems, through soil construction work, mechanical and biological injuries, compaction caused by vehicle and human's activities, poor planting conditions and pollution. This situation can cause serious damage to the root system, exposing urban trees to a high hazard risk, exposing buildings, public utilities and human to a significant danger.

However, although it is understood that the structure of the forest plays a vital role in determining its effectiveness as a protective barrier against natural hazards (Jahn 1988, Kräuchi et al. 2000), little research was carried out related to the mechanical resistance of different tree species to different types of soil and environment, as well as to natural hazard e.g. rockfall, avalanches and wind and snow loading. Therefore, more knowledge on the anchorage and root morphology of different landscape species is urgently needed in order to provide further insight into the understanding the anchorage mechanics and how they are related to their function. Once this knowledge is clearly understood, it can be utilized in selection and production of trees which are resistant to wind or other natural type of hazards and subsequently in the management of these trees.

Root system and anchorage mechanics of mature tree

Increasing damage to forest and urban trees due to the frequency of catastrophic storms in recent years (Quine 1995) has led to an interest in research into tree stability and anchorage mechanics empirically (Coutts 1983, 1986, Crook and Ennos 1996, Mickovski and Ennos 2002, 2003, Stokes 1999, 2000, Cucchi et al. 2004). Different mechanisms of anchorage failure have been identified, depending on its external shape and internal wood properties, local climatic conditions (Coutts 1983, 1986, Fraser and Gardiner 1967, Petty and Swain 1985), root morphology and architecture (Crook et al. 1997, Ennos 1989, Stokes et al. 1999), and the soil where the tree was embedded (Dupuy et al. 2005b, Fourcaud et al. 2008). Root mechanical behavior is strongly influenced by the architecture of the root system (Stokes and Mattheck 1996), environmental conditions (Nicoll et al. 2006) and the biomechanics of the root tissue/tissue cellular structure (Watson et al. 1999), meanwhile the forces a plant must withstand will probably determine the shape of root system it develops (Ennos and Fitter 1992). In order to resist these external forces, trees must transfer these forces down the roots into the soil, as directly as possible (Stokes 2000). Therefore, woody plants must have at least one rigid element in the root system to act as a lever (e.g. deep taproot) or by forming a rigid root-soil plate in order to provide anchorage and stability for the tree. There are distinct ways in which this can be achieved in different tree species by having three main root system types. Three types of basic shapes of the root system can be found (Büsgen et al. 1929) depending on its three-dimensional form.

The first type of the root system a ‘plate’ or sinker system, often found in gymnosperms, which consist of horizontal lateral roots spreading out from the base of the tree stem (Figure 1.1a), becomes more efficient at larger sizes, due to the weight of the root-soil plate (rises with the fourth power of the linear dimensions compared to the third power for the taproots) (Ennos 1993, Nicoll et al. 1995, Stokes et al. 1995). The second type is ‘heart’ system (Köstler et al. 1968), usually found in large trees and the most common found in angiosperm where horizontal and vertical laterals develop from the base of the tree (Figure 1.1b) are considered to be the most efficient types of root system when concerning tree stability (Stokes et al 2000). Both type of root system (heart and plate) resist uprooting initially by the weight of the root and soil mass (Stokes and Mattheck 1996). A third type of root system is ‘taproot’ system (Figure 1.1c) consist of a large tap root which anchor the tree directly like a stake in the ground and horizontal lateral roots which act like guy ropes (Ennos 1993). Both tap root and horizontal lateral roots can be found in young trees, the tap root may cease to grow in older trees and lateral roots become relatively larger (Köstler et al. 1968) and contribute to important component of anchorage. Trees with heart and tap root systems have been classified as being the most resistant to uprooting and plate systems the least resistant (Stokes 2002, Dupuy et al. 2005b).

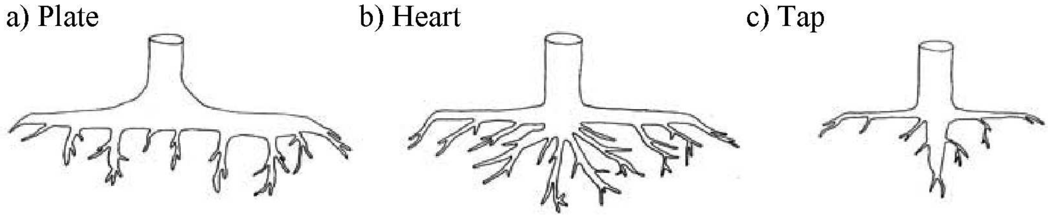



Figure 1.1. Different types of root system architecture a) 'plate' or 'sinker' system b) 'heart system' and c) 'tap' root system (after Stokes and Mattheck 1996).

However, in some species, such as in *Pinus*, the tap root continues to grow with the rest of the tree, and together with the sinker roots, they provide a significant component of anchorage (Danjon et al. 2005). However, despite being categorized into three main groups, some species may be be classed as having a mixture of root system types (Stokes 2002). These shape of root system can be modified depending on site conditions, from taproot type to sinker, superficial, and plate root system (Gruber 1994, Puhe 1994, Stokes and Mattheck1996) as can be found in many broadleaved and conifer species due to unfavorable conditions such as high water table, high bulk density, indurations or the presence of hard or iron pans (Coutts 1987, Moffat et al. 1998, Danjon et al. 1999). Such types of root system are poorly anchored in the soil, and subsequently reduced root anchorage and tree stability. Table 1.1 shows a list of tree species with different types of root systems commonly found in the temperate environment.

Table 1.1. Types of root system commonly found in different forest tree species in temperate environment (from Stokes 2002).

| Type of root system | | |
|---|---|---|
| **Plate** | **Heart** | **Tap** |
| (*Betula pendula* Roth.)[a] | *Acer campestre* L. | *Abies alba* Mill. |
| *Fraxinus excelsior* L. | *Acer platanoides* L. | *Juniperus communis* L. |
| *Picea abies* L. | *Acer pseudoplatanus* L. | (*Quercus sp.*)[a] |
| *Picea sitchensis* Bong. | *Alnus glutinosa* L. | *Pinus contorta* Dougl. |
| *Pinus cembra* L. | *Alnus incana* L. | *Pinus nigra* Arnold |
| *Pinus radiata D.* | *Betula verrucosa* Ehrh. | *Pinus pinaster* Ait. |
| *Pinus strobus* L. | *Carpinus betulus* L. | *Pinus sylvestris* L. |
| (*Populus sp.*)[a] | *Crateagus monogyna* Jacq. | *Pyrus pyraster* Burgsd. |
| *Populus tremula* L. | *Castanea sativa* Mill. | (*Robinia pseudoacacia* L.)[a] |
| (*Robinia pseudoacacia* L.)[a] | *Larix decidua* Mill. | *Sorbus terminalis* L. |
| (*Sorbus aucuparia* L.)[a] | *Larix leptolepis* Sieb. | |
| | (*Populus sp.*)[a] | |
| | *Prunus avium* L. | |
| | *Pseudotsuga menziesii* Mirb. | |
| | *Pseudotsuga taxifolia* Britt. | |
| | *Quercus petraea* Liebl. | |
| | *Quercus robur* L. | |
| | *Quercus rubra* L. | |
| | *Taxus baccata* L. | |
| | *Tilia cordata* Mill. | |
| | *Tilia platyphyllos* Scop. | |
| | *Ulmus effusa* Willd. | |
| | *Ulmus glabra* Huds. | |
| | *Ulmus Montana* | |

[a]Name in brackets can commonly be found with that type of root system, depending on local conditions.

The anchorage and stability of different types of root systems

Vulnerability to overturning has been investigated at stand or individual tree level in many temperate forest species. At stand level, the damage is correlated to a certain stand characteristics i.e tree species, silviculture treatment and practice, soil type and wind speed (Putz et al. 1983, Ruel et al. 2000). However, the finding from these studies were found to be inconclusive to reasons why some trees snap, overturn or remain undamaged within a relative small geographic area (Dunham and Cameron 2000). Furthermore, such analysis is incomplete due to the numerous variables influencing tree stability, which are not taken into account e.g. root system or soil characteristics and soil hydrology (Dupuy et al. 2005b). These limitations, however, can be solved where the mechanisms of tree stability involving the resistance of root anchorage to uprooting and the influence of root anchorage on tree stability can be determined and investigated using static tree pulling tests (Coutts 1986) where trees were winched sideways using a winch and cable system until failure and measuring the force to a certain point and required to cause failure (Crook and Ennos 1996, Papesch et al. 1997, Stokes 1999, Moore 2000, Peltola et al. 2000, Mickovski and Ennos 2003, Cucchi et al. 2004, Nicoll et al. 2005, Stokes et al. 2005a,b). From the test, the anchorage stiffness and critical turning moment needed to uproot or break the tree can be calculated, quantified and related to various characteristics, e.g. species, stem weight, tree dimension (DBH and height), soil type, forest treatment, stand density, root depth, topology and biomass are all important factors to consider when examining tree anchorage. Even if this method does not really simulate wind loading due to the lack of dynamic sway (Oliver and Mayhead 1974, Gardiner et al. 1997), there seems to be no differences in the type of damaged roots between winched or windblown trees (Coutts 1983).

In static tree pulling test (see review Peltola 2006), a simulated static force causes deflection of the tree stem (Figure 2.2, Chapter 2). The leaning stem then assists in uprooting the tree because its center of gravity moves over the hinge point in the root system (Ray and Nicoll 1998). The second uprooting force is provided by the mass of the deflecting stem and the crown. However, the uprooting moment is resisted by bending of the tree stem and various components of root anchorage. If the uprooting moment exceeds the resistive bending moment of the tree at a particular angle of deflection, the tree will deflect further and finally uproot or stem breakage. In these circumstances, the relative strengths of the roots and stem will determine the mode of failure. From these tests, the critical turning moment needed for uprooting or stem breakage can be calculated based on the recorded forces and the factors influencing the resistance of tree to uprooting or stem breakage can be determine by regression analysis between the maximum resistive bending moment and various tree physical characteristics such as DBH, tree height, stem volume, root plate diameter, root CSA and root depth (Fraser 1962, Somerville 1979, Papesch et al. 1997, Gardiner et al. 2000, Meunier et al. 2002). This critical turning moment allows comparisons between species due to their different mechanical behaviour (Savill 1976, Peltola et al. 2000), which could be explained by stem characteristics, e.g. taper (Meunier et al. 2002) or root system architecture and anchorage strength (Stokes 1999).

Fraser (1962) and Fraser and Gardiner (1967) were among the pioneers to have measured the forces required to pull trees in the field using tree pulling test. Fraser and Gardiner found that bending moments at the base of the tree (*Picea sitchensis* Bong Carr.) in the region of 40-52 kNm would lead to uprooting. In these studies, a significant linear relationship was found between the maximum resistive bending moment and the stem mass of Sitka spruce, rooting depth and soil type. Meanwhile, Coutts (1986) recorded values of 10-50 kNm. Both experiments were carried out on *Picea sitchensis*. Other previous studies have also shown significant relationships between maximum resistive bending moment and various tree physical characteristics (see review in Peltola 2006) growing on different environments. It has also been reported in the literature that anchorage strength of trees mainly depend on the properties of root systems such as root architecture and morphology (Nicoll and Ray 1996, Stokes et al. 1998, Stokes 1999, Mickovski and Ennos 2003, Di Iorio et al. 2005, Chiatante et al. 2005, Danjon et al. 2005), types of root system present (Stokes and Mattheck 1996, Stokes 2000, 2005) soil conditions (Moore 2000, Ennos 1990, Goodman and Ennos 1999, Dupuy et al. 2005b) and stand characteristics such as tree species, tree size, stand quality and location and forest treatment (Somerville 1979, Stokes 1999, Peltola et al. 2000, Cucchi et al. 2004, Mickovski and Ennos 2003, Stokes et al. 2005).

However, using similar technique, the most important components of root anchorage were investigated by Coutts (1983, 1986). Four major components of the root system (Figure 1.2) contributing to tree stability and resisting uprooting in shallow-rooted Sitka spruce were identified: (1) the weight of the root-soil plate which provide the initial resistance to overturning, (2) the resistance of the soil underneath and around the edge of the plate, (3) the tensile strength of the roots on the windward side of the plate, and (4) the resistance to bending of the leeward roots. Coutts (1983, 1986) also highlighted that the most important component of anchorage in resisting overturning was the roots on the windward side, which accounted for approximately 60% of the total anchorage. Trees with shallow-plate systems such as Sitka spruce and Norway spruce therefore generally uproot at lower loads, with the root plate being completely lifted out of the ground.

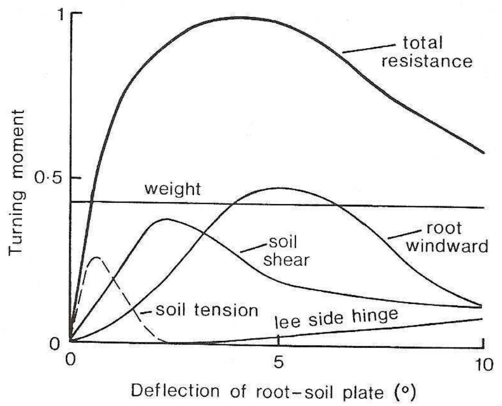



Figure 1.2. Components of anchorage during uprooting in shallow-rooted Sitka spruce (after Coutts 1986).

However, a similar study to that of Coutts (1983, 1986) conducted by Crook and Ennos (1996) on deep-rooted ('heart' root system) hybrid larch trees (*Larix europea* x *japonica*) found that approximately 75% of the anchorage strength was provided by the windward sinker and tap root, thus indicating that the presence of the taproot may further increase the strength of root anchorage. An investigation by Crook and Ennos (1997) on the anchorage mechanics of tropical taprooted species (*Mallotus wrayi*) found different mechanisms of failure in this type of root systems. During overturning, the tree rotates and bends on the windward side of the taproot (Figure 1.3a). The taproot itself pushes into the soil on the leeward side, the top half rotating, and the bottom half remaining reasonably well-anchored. A crevice is then formed on the windward side, becoming larger as the tree is pulled over (Crook and Ennos 1997). Hintikka (1972) reported that the lower half of the taproot of *Pinus sylvestris* may make a similar semicircular movement and push into the soil on the windward side (Figure 1.3b). In such a case, the taproot is firmly attached to the soil at its distal end, and the lateral roots hold the stem so rigidly that the taproot has to move in the opposite direction. In this situation, trees with shorter taproots can easily rotate without mobilizing the full strength meanwhile longer and narrow taproots can easily break without mobilizing the full soil resistance (Mickovski 2002). Thus, trees with well developed heart and tap root system which fail in the root system, usually fail with the root-soil ball not lifted out of the ground, however the mode of failure does appear to depend on tree age (Cucchi et al. 2004). In order to gain further insight on the behavior of the root system when subjected to mechanical loading, strain gauges were used on several forest species (Ennos 1995, Crook and Ennos 1996, Stokes 1999, 2000). The results suggested that in trees which broke in trunk, strain was always found to be higher in the stem than in roots, whereas in trees which broke at the stem base or uprooted, strain was always highest at the base of the trunk or in the root system, respectively. Therefore, the results showed that tree species which fail in the trunk under loading are better anchored than tree species that fail in the root system.

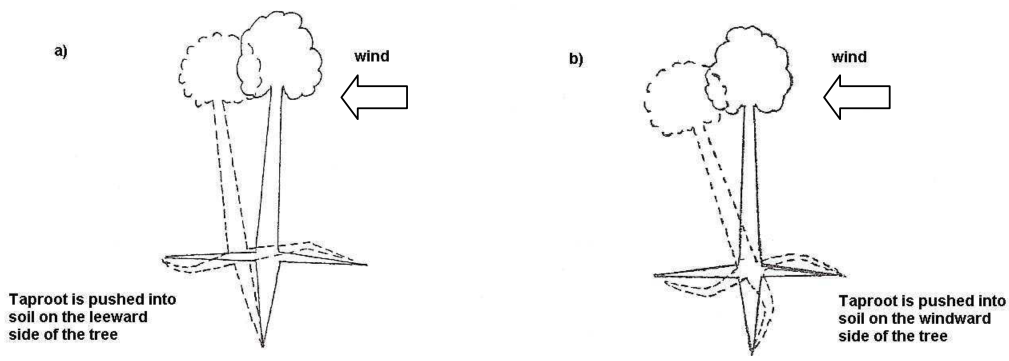



Figure 1.3. Overturning mechanisms in taprooted trees (a). the taproot may be pushed into the soil on the leeward side of the tree, leaving a crevice in the soil (From Crook and Ennos 1997). (b). In certain cases, the taproot may push into the soil on the windward side of the tree, but still be firmly anchored in the soil by its distal end (From Hintikka 1972) (from Stokes 2002).

The influence of root system architecture on root anchorage and tree stability

The architecture of the root system influences anchorage and is an important factor of tree stability (Coutts 1983). Root architecture is an important consideration in terms of the way which forces on the tree structure are transferred into the ground (Stokes 2005) and the allocation of biomass among roots would be expected to have a large effect on tree stability (Coutts 1983b). Root system asymmetry increases along with the variability of the root system as trees age (Sutton 1969), as a result of the variety of stimuli the tree experiences, and this might significantly reduce the overall stability of a tree (Coutts et al. 1998). When the mechanical stress is not homogenously distributed around the root system, root growth and development may be increased in the direction of maximal stress intensity influencing the symmetry of anchorage rigidity around the stem (Coutts 1983, Nicoll and Ray 1996, Chiatante et al. 2003b). Where roots are clustered asymmetrically around the root plate, trees may be overturned relatively easily if they are loaded in a direction other than that of the center of mass. Tree stability may also be reduced in trees in which structural roots are poorly developed or even missing on one side (Coutts 1983). Root asymmetry can result from asymmetric origin and growth of primary roots (Coutts et al. 1998), and this can be affected by several external factors, including water and nutrient supply (Coutts 1987, Mickovski and Ennos 2002), flexing of the roots during wind loading (Nicoll and Ray 1996, Stokes et al. 1995a, Danjon et al. 2005), and topography (Chiatante et al. 2005, Di Iorio et al. 2005, Nicoll et al. 2006). Two types of root system asymmetry were described by Coutts et al. (1998). Type I (Figure 1.4a) shows regular arrangement of individual roots around the stem center, but roots vary in diameter, meanwhile in type II (Figure 1.4b), roots are not uniformly arranged but evenly sized. In tree root systems, both types of asymmetry may often occur together as part of an adaptation to environmental or mechanical loading, causing clustering of roots in a preferred direction (windward, leeward, up-slope or down-slope) and differs between studies (Nicoll and Ray 1996, Watson 2000, Chiatante et al. 2003b).

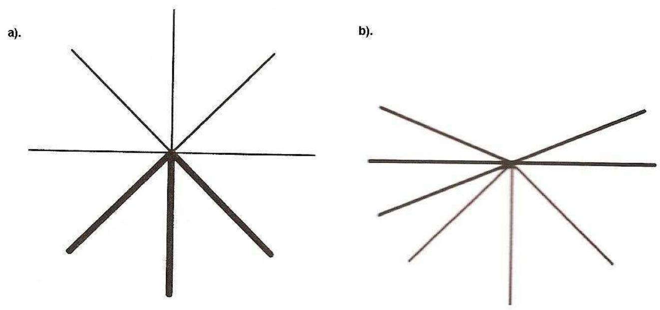



Figure 1.4. Types of asymmetry of tree root system; a). Type I, a regular arrangement with variation in diameter, b). Type II, irregular arrangement with uniform diameter (Coutts et al. 2000).

Root symmetry has previously been measured in terms of center of mass of all lateral roots, weighted by diameter or CSA of roots (Quine et al.1991, Nicoll and Ray 1996, Mickovski and Ennos 2003). Studies on root asymmetry have produced variable results. Somerville (1979) showed that the root distribution was very close to symmetry in the root system of *Pinus radiata* in New Zealand, meanwhile in another studies in Europe (Coutts et al. 1990, Nicoll and Ray 1996, Drexhage et al. 1999, Mickovski and Ennos 2003, Di Iorio et al. 2005, Nicoll et al. 2006) have shown that the root systems are significantly asymmetric, with a clustering of roots in a preferred orientation such as prevailing wind direction or slope direction (Nicoll and Ray 1996, Di Iorio et al. 2005, Nicoll et al. 2006, Soethe et al. 2006).

Mechanical stress can play a fundamental role in the development of root structures, causing significant changes to the allocation rules that act to optimize tree stability (Nicoll et al. 1995, Stokes et al. 1998). Tree roots are known to be very sensitive to mechanical loading, and respond to external stresses by laying down wood in areas susceptible to rupture (Mattheck 1998, Nicoll and Ray 1996, Stokes and Guitard 1997). Root cross-sectional area (CSA) has been considered as playing a major role in tree anchorage, particularly in roots close to the stem (Nicoll and Ray 1996, Coutts et al. 2000, Nicoll 2000, Chiatante et al. 2003, Danjon et al. 2005). Mechanical stresses may cause modification of the shape of root CSA (Coutts et al 1998, Crook and Ennos 1996, Mickovski and Ennos 2003, Chiatante et al. 2005) which resemble T- or I-beam shaped (Rigg and Harrar 1931, Nicoll and Ray 1996) or eccentric shaped (Mickovski and Ennos 2003) where structural are utilized in an optimum manner using minimum of material. Such changes in root *CSA* can resist bending and compression stresses more efficiently within the soil more than any other shape with a similar *CSA* (Nicoll 2000, Table 1.2) and further increase rigidity of the root soil plate (Nicoll and Ray 1996). Conifers, when wind stressed are known to allocate a higher proportion of biomass to the lower stem and adjoining roots. Consequently, lateral root immediately adjacent to the stem increase diameter growth (Coutts et al 1998, Nicoll and Dunn 2000), which will result in root stiffening and a subsequent increase in the rigidity in that area of the root. An extreme case of eccentric roots is buttressing (Crook et al. 1997). Although there is a numerous literature recorded, only a limited number of studies have correlated tree mechanical data and root architecture (Coutts 1983, 1986, Stokes 2002, 2005a,b, Crook and Ennos 1996, Mickovski and Ennos 2003, Khuder et al. 2007). Such studies are laborious and time consuming and are not easy to interpret due to the complexity of the mechanisms that exist in both, the root systems and soil as well as their multifactorial aspect (Danjon 2005, Stokes et al. 2005).

Table 1.2. Second moment area ($I$) and estimated flexural stiffness (vertical flexing) for different root shapes with the same area (from Nicoll 2000).

| *Shape* | $I_{xx}$ ($m^4$) | $I_{yy}$ ($m^4$) | $\%I_{xx}$ | $\%I_{yy}$ | Flexural stiffness $EI$ ($Nm^2$) |
|---|---|---|---|---|---|
| 1. 'I-beam' root section (12875 $mm^2$, depth 195 mm, width 87 mm) | 40.259 | 5.367 | 100 | 100 | $2.4 \times 10^5$ |
| 2. 'T-beam' root shape with same area as shape 1. | 33.787 | 5.727 | 84 | 107 | $2.0 \times 10^5$ |
| 3. Rectangle with same area and ratio of width to depth as 1. | 30.962 | 6.163 | 77 | 115 | $2.4 \times 10^5$ |
| 4. Elliptical section of same area as 1. (depth 195 mm) | 30.598 | 5.687 | 76 | 106 | $1.8 \times 10^5$ |
| 5. Circular section of same area as 1. (diameter 128 mm) | 13.191 | 13.191 | 33 | 246 | $7.9 \times 10^4$ |

In order to assist in the interpretation of complex experimental data or in testing and identifying parameters that need to be studied, an alternative to difficult field experiments is through modelling approaches, such as numerical modelling using the Finite Element Method (Dupuy et al. 2005b, Fourcaud et al. 2008). Using this type of analysis, certain parameters such as shoots, roots and the local soil environment, could be analysed and modified easily to determine the effect of these parameters on tree anchorage, and studied simultaneously (Fourcaud et al. 2008). Based on the data available as well as an understanding on the biomechanical behaviour of the tree and mechanisms of root anchorage, attempts have been made to develop mechanistic models for predicting the critical windspeed at which trees are likely to be uprooted or broken (Peltola and Kellomäki 1993, Peltola et al. 1999) in order to provide tools for assessing the risk of wind and snow damage in the area of forest management. However, due to the complexity of the mechanisms involved in the components of root anchorage and tree stability, much basic research is still needed in the area of forestry and arboriculture in order for us to better manage our valuable landscape trees.

However, most studies on root anchorage have concentrated on forest species of commercial interest, particularly conifers grown in a temperate environment (Crooks and Ennos 1996, Nicoll and Ray 1996, Stokes 1999, Watson 2000, Moore 2000, Cucchi and Bert 2004, Mickovski and Ennos 2003a,b). Very few studies were done on urban or other landscape species, particularly related to the protection against natural or man-made hazards growing on different environment. Therefore, more knowledge about root morphology and architecture of other species is necessary to provide further insight into the way in which the form is related to the function of root systems (Mickovski and Ennos 2003b).

In an attempt to identify and resolve some of the inconsistencies pertaining to the anchorage mechanics of different trees growing on different conditions, this study was initiated with the aim to investigate the biomechanics and root system architecture of different tropical and temperate landscape tree species grown on two different environmental conditions with intrinsically different root architectural patterns. The study was divided into two parts: the first part investigated the effect of root loss through mechanical trenching on mature tropical urban tree (*Eugenia grandis* Wight) and temperate tree species of *Pinus pinaster* Ait with intrinsically different root architectural patterns. The second part of the study was carried out in order to understand the overturning mechanism and mechanical resistance on three different on tree species: Silver fir (*Abies alba* Mill.*),* European beech *(Fagus sylvatica* L.*)* and Norway spruce *(Picea abies* L.) growing in a mixed forest stand in the French Alps region to rockfall and wind loading. In both studies, the most significant predictors were also determined and correlated with tree anchorage. Results from this study are discussed with regards to providing advice and guidelines in better managing of our valuable landscape areas in order to meet the long-term objectives of the tree planting programme.

Organization of the Thesis

This thesis is organised into five chapters. The main chapters of the thesis (chapter 2, 3 and 4) are presented in a format of a manuscript and series of papers. The layout of each chapter is structured as follows:

Chapter 1 describes a general background of the study, its significance and importance. A comprehensive literature on root anchorage were reviewed and reported, methods and factors that influence root anchorage are also discussed in this section. It also presents the objectives of the study as well as the organization of the thesis.

Chapter 2 and 3 covers a study on root architecture and the effect of root loss through trenching on the anchorage of mature tropical urban trees (*E. grandis* Ait) and deep-rooted temperate species (*P. pinaster* Ait). The materials and methodology were discussed, together with the details on the calculations and statistical analysis employed. By combining the results obtained from the mechanical test and root architecture, the parameters that most influence root anchorage were determined. Results were discussed into two sections. The first section of the results discussed the effect of root loss through trenching on anchorage and rotational stiffness of the root system, whilst the second section correlates the results from mechanical tests with various shoots and roots parameter. The finding and the implication of the results were compared to previous research and provided guidelines for the arborist in dealing with potential hazard trees under their jurisdiction.

Chapter 4 deals with the study to determine the most important characters associated with mechanical resistance to rockfall and wind loading on three tree species: Silver fir (*Abies alba* Mill.), European beech (*Fagus sylvatica* L.) and Norway spruce (*Picea abies* L.) in a mixed forest stand in the French Alps region. Strain gauges were attached to the stem lateral root to determine the distribution of strain within the tree during overturning and root morphology measured for all uprooted tree. Static winching tests were used to pull the trees both up- and downhill and finally to failure. Results were compared with previous findings and discussed with regards to providing knowledge and better understanding on how different tree species adapt to wind loading and resistance to rockfall.

Finally, Chapter 5 concludes the findings of the research and states the recommendations for further research.

# CHAPTER 2: THE EFFECT OF ROOT ARCHITECTURE AND ROOT LOSS THROUGH TRENCHING ON THE ANCHORAGE OF TROPICAL URBAN TREE (*Eugenia grandis* Wight)

Abstract

*Eugenia grandis* (Wight) is grown in urban environments throughout Malaysia and root systems are often damaged through trenching for the laying down of roads and utilities. We investigated the effect of root cutting through trenching on the biomechanics of mature *E. grandis*. The force necessary to winch trees 0.2 m from the vertical was measured. Trenches were then dug at different distances (1.5, 1.0 and 0.5 m) from the trunk on the tension side of groups of trees. Each tree was winched sideways again and the uprooting force recorded. No trenches were made in a control group of trees which were winched until failure occurred. Critical turning moment ($TM_{crit}$) and tree anchorage rotational stiffness (TARS) before and after trenching were calculated. Root systems were extracted for architectural analysis and relationships between architectural parameters and $TM_{crit}$ and TARS were investigated.

No differences were found between $TM_{crit}$ and trenching distance. However, in control trees, significant relationships only exist between $TM_{crit}$ and both single and combination of parameters e.g. stem dimensions (DBH and tree height), rooting depth, no of laterals and root plate size. TARS was significantly decreased when roots were cut at 0.5 m only. Surprisingly, no relationships existed between $TM_{crit}$ and TARS with any root system parameter when trenching was carried out at 1.0 m. Our study showed that in terms of TARS and $TM_{crit}$, mechanical stability was not greatly affected by trenching, probably because rooting depth close to the trunk was a major component of anchorage.

Key words: biomechanics, anchorage rotational stiffness, critical turning moment, mechanical stability, acclimation, root eccentricity.

Introduction

The presence of trees in urban areas provides many benefits for both the community and environment (Bernatzky 1978, Bradshaw et al. 1995, Miller 1997, Thomas 2000). However, due to their close proximity to infrastructure, mature or large trees can pose significant risks and liabilities especially in an era where the consequences of climate change include an increase in windstorms and hurricanes (Quine 1995, Deborah et al. 1996). Therefore, urban trees require special attention, in particular with regard to mechanical stability. Trees in towns and cities are often subject to severe environmental stresses and mechanical damage, especially to root systems, through soil compaction under roads or paving, poor planting conditions, pollution and construction work. With regard to the latter constraint, roots can be heavily damaged through the laying of foundations and trenching during e.g. construction works and installation of underground utility lines. As most of a tree's roots are found near the soil surface, cutting of roots through trenching can cause serious damage to the root system, resulting in the possible decline or death of the tree. Depending on the distance of the trench from the stem, mechanical stability of the tree may also be compromised (Miller and Neely 1993, Brudi and Wassenaer 2002). Whilst a healthy, vigorous tree can withstand removal of up to 50% of its roots (Heliwell 1985, Sinclair et al. 1987), tree stability may nevertheless be reduced if all the roots on one side are severed (Heliwell 1985), or if structural root development is asymmetrical (Coutts 1983, Coutts et al. 2000). The danger of uprooting is thus very high when lateral roots of large trees are severed within approximately 1.0 - 1.3 m of the trunk (Wessolly and Erb 1998). This scenario is extremely critical for urban trees where growing space is restricted and soil conditions are not optimal, resulting in root systems which are often shallow or deformed.

For trees growing in built-up environments, the risk posed by mechanical instability depends largely on the hazard factor and resulting consequences of tree failure. Where human lives and infrastructure are at risk from trees toppling or losing their branches during storms, those trees will be inspected frequently and pruned or removed as necessary. However, the root system is much more problematic to manage, largely due to the difficulty in investigating it *in situ* and carrying out experimental studies on this hidden part of trees. To our knowledge, there is little published research on how much root loss a tree can withstand without seriously compromising mechanical stability (Coutts 1983, 1986, Fourcaud et al. 2008), nor at what distance from the trunk digging or trenching can be carried out without increasing the risk of failure. Arborists often use above-ground tree features to specify the dimensions within which root systems should not be damaged. Simple calculations involving branch spread (Bernatzky 1978, Olson and Wray 1979, Schoeneweiss 1982, Tartar 1989, Fazio 1992, Miller and Neely 1993), trunk diameter (Morel 1984, Mattheck and Breloer 1995) and tree height (Miller et al. 1993) are commonly used. Current recommendations as proposed by the British Standard Institute (1989) and Watson (1990) suggest a minimum distance for trenching along one side of the tree of 0.15 m for each 0.025 m diameter at breast height (DBH), whereas Harris (2004) and the American Society of Consulting Arborists (1989) recommend 0.30 m for each 0.025 m DBH (Miller and Neely 1993). Mattheck and Breloer (1995) have also recommended an equation whereby the minimum distance equals the root plate diameter, which in turn is correlated with trunk diameter. Whilst these guidelines may be helpful, advice for arborists concerning the minimum 'safe' distance between a trench and a tree is conflicting. These guidelines have also been developed based on observations of trees and site characteristics after failure occurred and have not been based on sound experimental procedures. As a result, arborists are often in the dilemma of making the decision whether to retain or remove large trees from sites where construction or trenching is carried out close to the tree. Therefore, a rigorous investigation of the influence of root loss through trenching on tree mechanical stability is required. Although a large body of information on tree resistance to windthrow is available in the forestry literature (see review by Peltola 2006), few data exist for urban trees (Bell et al. 1991, Roodbaraky et al. 1994, Mattheck 1998), particularly in tropical areas which are frequently subjected to heavy storms and cyclones.

In temperate forest trees, the relationship between tree resistance to overturning and root morphology has been much elucidated in recent years (Danjon et al. 2005, Dupuy et al. 2005a,b, 2007, Fourcaud et al. 2008, Khuder et al. 2007). Through static bending tests, tree behaviour in a wind storm can be simulated (Achim et al. 2005, Mickovski and Ennos 2003, Cucchi et al. 2004, Nicoll et al. 2005, Stokes et al. 2005, Peltola 2006), although few studies then include an investigation of root architecture (Mickovski and Ennos 2003, Stokes et al 2005, Dupuy et al. 2007, Khuder et al. 2007). By combining information from bending tests and architectural analysis, it is possible to identify those characteristics influencing uprooting the most. Nevertheless these features depend on species, soil type and planting treatment (Fourcaud et al. 2008, Khuder et al. 2007). A more laborious but practical method for investigating the influence of root system characteristics on tree anchorage is to observe the effect of root removal on resistance to overturning during bending tests (Coutts 1983, 1986, Crook et al. 1997). In urban trees, such a method could be used to determine the effect on anchorage of root removal through trenching. Together with data on root system morphology, the minimum and maximum distances for disturbing and cutting roots of mature trees could be determined.

We carried out a study whereby roots were cut through trenching in the tropical urban species *Eugenia grandis,* Wight, grown on sandy clay soil in an urban park in Kuala Lumpur, Malaysia. In a series of tests where roots were removed and then winched sideways to failure, we quantified the influence of root loss on tree anchorage. Root morphology was then measured and characteristics correlated with anchorage rigidity. Results are discussed with regard to providing guidelines and advice for the arborist dealing with potential hazard trees in towns and cities.

## Materials and Methods

### Site details

The study area was located in the urban park of Taman Tasik Permaisuri (49.4 ha), in the district of Cheras, 15 km south-east of Kuala Lumpur (03°05'81N", 101°43'26"E, 79 m above sea level). The site, measuring 31 x 150 m plot with a density of 151 *Eugenia grandis* Wight was established in 1984 as part of the "Greenery and Beautification Programme" conducted by the City Hall of Kuala Lumpur. This species were chosen for the study due to its popularity as urban landscape trees, the size of the trees that had reached mature size and therefore can posed a significant risk to the user. Furthermore, no attempt was made to study the anchorage strength of the tree. The plot was situated on a south-west facing slope with an angle of 7 - 10° and was sheltered from prevailing winds from south-west (SW) and north-east (NE) directions. Generally, Malaysia has two main seasons, the north-east Monsoon (November - March) and the south-west Monsoon (May - September), separated by two relatively shorter inter-monsoon periods. Wind data monitored 25 km away, at Subang (Table 2.1), showed that the site was subjected to prevailing winds from different directions, depending on the time of year. In May - September, prevailing wind direction was from the SW, but this changed to NE from November - March. Mean windspeed in May - September is 1.5 $ms^{-1}$ and from November to March is 1.7 $ms^{-1}$. However, the strongest winds of 35.5 $ms^{-1}$ recorded over a 20 year period came from the NE (300°) and occurred during the inter-monsoon season, in the month of October (Malaysia Meteorological Department). Air temperature is monitored at a weather station 8 km away (TUDM Sungai Besi, Kuala Lumpur). The climate is tropical with high temperatures and air humidity all year round. The site experiences an annual mean temperature of 28.4°C (in 2003), with the highest monthly mean temperature of 33.8°C (in March) and the lowest of 23.7°C (November-December). In 2004, total annual rainfall was 2819.4 mm and it rained 242 days in the year. Soil at the site was a sandy clay soil and no hard pan or seasonal waterlogging exists, therefore root growth was not restricted vertically.

Table 2.1. Summary of 30-year (1975- 2005) wind statistics monitored at Subang Airport showing the annual percentage frequency of wind speeds in various directions (Malaysia Meterological Department).

| Windspeed ($ms^{-1}$) | Mean percentage frequency of wind speeds in different directions (1975-2005) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | N | NE | E | SE | S | SW | W | NW | CALM | Total |
| < 0.3 | - | - | - | - | - | - | - | - | 36.5 | 36.5 |
| 0.3 - 1.5 | 7.0 | 2.3 | 3.9 | 2.4 | 2.8 | 2.0 | 2.4 | 4.9 | - | 27.7 |
| 1.6 - 3.3 | 3.2 | 0.8 | 2.0 | 2.1 | 3.9 | 2.6 | 2.8 | 4.0 | - | 21.4 |
| 3.4 - 5.4 | 1.1 | 0.2 | 0.4 | 0.8 | 2.7 | 1.6 | 2.6 | 2.0 | - | 11.4 |
| 5.5 - 7.9 | 0.1 | 0.0 | 0.0 | 0.0 | 0.3 | 0.2 | 0.4 | 0.3 | - | 1.3 |
| > 8.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | - | 0.0 |
| Mean % frequency of windspeed. | 11.4 | 3.3 | 6.3 | 5.3 | 9.7 | 6.4 | 8.2 | 11.2 | 36.5 | |

Tree selection and experimental layout

In April 2005, a total of 28 trees were randomly selected from a plantation of 20 year old *E. grandis* (Figure 2.1). Trees were planted in 1984 as seedlings at approximately 4 m intervals. In 2005, stem diameter at breast height (DBH) was 0.21 ± 0.02 m, tree height was 13.80 ± 0.96 m and crown spread was 3.9 ± 0.17 m (means ± standard error). A complete randomised design (CRD) was used to divide trees into four groups. Each group consisted of seven trees and was subjected randomly to three different soil trenching treatments. No trenching was carried out on control group trees.

Figure 2.1. A 20-year old *Eugenia grandis* Wight stand in the study area at the Taman Tasik Permaisuri, Cheras, Kuala Lumpur, Malaysia.

Tree winching and trenching tests

Tree winching tests were carried out early April 2005 to determine the effect of root loss through trenching on root system anchorage. The tests were carried out when precipitation was maximal, therefore soil moisture content was high. Higher soil moisture content results in lower soil shear strength (Crook and Ennos 1997) therefore failure through winching is more likely to occur in the root system than in the trunk. To remove the confounding parameter of trunk weight and crown area on anchorage (Coutts 1986) the trunk was cut at a height of 2 m above ground level.

The winching tests (Figure 2.2) were similar to those carried out in previous studies (Coutts 1986, Crook and Ennos 1996, Papesch et al. 1997, Stokes 1999, Moore 2000, Peltola et al. 2000, Mickovski and Ennos 2003, Cucchi et al. 2004, Nicoll et al. 2005, Stokes et al. 2005). A sling was looped around the trunk of the test tree at a height of 1.8 m. This sling was connected to the winch cable and a hand held winch (maximal force capacity of 32 kN) and attached to the base of an anchoring tree. A pulley attached between the tree and the winch was used to double the winch capacity. A force transducer capable of measuring force up to 20 kN (type K25H-20kN, Scaime S.A., France) was connected between the sling and the winch cable. Measurements of stem angle and force were recorded every second using dataloggers (Almemo 2290-8, Ahlborn, Germany). The distance between the test and anchor tree was measured, along with the azimuth direction in which the tree was pulled.

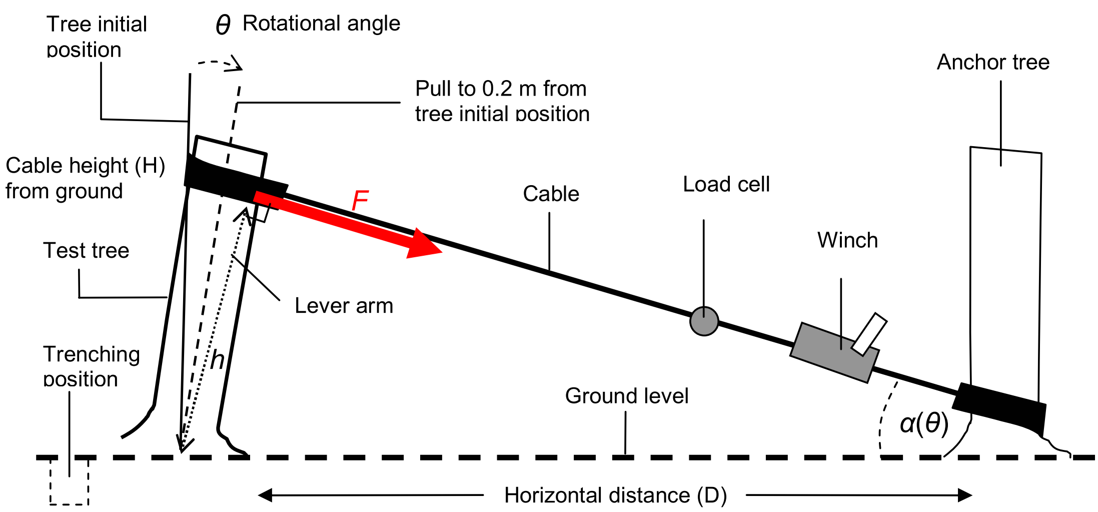



Figure 2.2. Trees were winched sideways and the force necessary was measured using a load cell located between the winch and anchoring tree. A trench was dug at a distance from tree, severing all lateral roots on that side of the tree.

To quantify the loss of anchorage rigidity through trenching, each tree was winched sideways (in a random direction) before and after trenching. For each test, the tree was pulled sideways to a distance of 0.2 m from its initial position (the amount of cable displaced during the winching test was used to measure the distance of 0.2 m). To test if this deflection was well within the tree's elastic limit, we carried out several loading and unloading tests on extra trees in the plot. The force required to pull the tree 0.2 m sideways was then measured. The tree was released and allowed to return to the vertical. Data were similar each time we winched the same tree to 0.2 m and then released it, before repeating the test (Figure 2.3). Therefore we assumed that no plastic damage had occurred. On test trees, a trench (1.0 m deep and 3.0 m long, extending 1.5 m from each side of the trunk) was dug on the counter-winchward (CW) side of each tree using a trenching machine (Figure 2.4) where the major lateral roots were cut off. The CW side of the stem was chosen as roots in this direction are held in tension contribute the largest resistance to overturning (Coutts 1983, 1986; Crook and Ennos 1996; Stokes 2002). Therefore, root loss on the CW side of the tree should have a greater effect on anchorage rigidity. Trench dimensions were enough to sever all roots on one side of the tree. For each tree, only one trench was dug at one of three different distances (0.5, 1.0 and 1.5 m) from the stem base. After the trench was made, trees were winched in the same direction until uprooting or stem breakage occurred. In control trees, no trenches were dug and trees were winched to a distance of 0.2 m and then until failure. Once the winching tests were completed, soil-root plate diameter (perpendicular to the winching direction) and depth were measured and the direction of slope recorded.

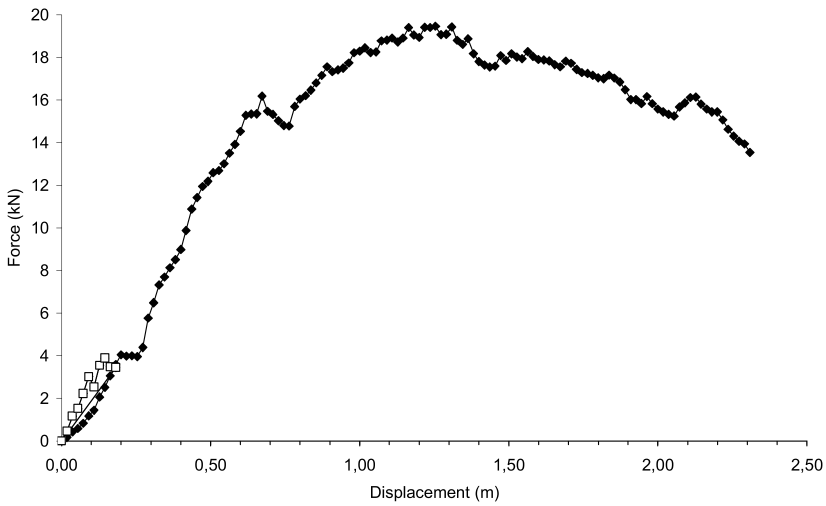



Figure 2.3. A typical force versus displacement graph for a control tree. The initial part of the curve (white squares) shows the tree winched sideways to a distance of 0.2 m. The second part of the curve (black diamonds) shows the tree winched until failure.

To measure root system morphology, trees were then excavated using a mechanical digger. Prior to the excavation, the stump of the study tree was marked according to the pulling direction and north. A 1.0 m deep trench was dug around the tree to sever the remaining roots and the mechanical digger then slowly removed the root system from the soil. Soil was removed from the root systems using a high pressure water jet. All broken roots were collected and tagged and taken together with the root systems to the laboratory for measurement of root morphology.

Figure 2.4. A mechanical trencher used during the trenching tests in Malaysia.

Soil measurements

Immediately after each winching test, soil samples were taken to determine if soil water content and bulk density differed between trees. For soil moisture analysis, samples (n = 19) were taken from three different depths within the soil-root plate (0.05 m, 0.30 m and 0.7 m). Samples were then weighed before drying the soil to a constant mass and weighing again (105°C for 24 hours or until no further changes in weight). Soil moisture content was expressed as a percentage (grams of water per 100 grams of dry soil).

To measure soil bulk density, a soil corer was used to take samples 70 mm long and 40 mm wide. Three samples were taken from five different locations within the *E. grandis* stand. Soil bulk density was obtained using the core method, where a core ring is pressed or hammered into undisturbed soil to the desired depth and then carefully removed to obtain a known volume of soil. The soil moisture content of each of these samples was measured using the method described above. Therefore, soil bulk density can be calculated for a known volume of soil using equation 1:

$$BD = \frac{Wb - Wr}{\pi h d^2 / 4} \qquad \text{(Equation 1)}$$

Where BD is the soil bulk density expressed as g $cm^{-3}$; *Wb* is the weight of the soil and core ring after oven-drying; *Wr* is the weight of the core ring; *h* is the core ring height or depth and *d* is the core ring diameter.

Measurements of root system morphology

Root system morphology was measured to determine if there was a relationship with tree anchorage rotational stiffness (*TARS*) and the critical turning moment ($TM_{crit}$). The shape, size and orientation of all structural roots (defined as any woody root with a diameter >10 mm) were quantified using techniques similar to those described by Nicoll and Ray (1996), Drexhage and Gruber (1998), Drexhage et al. (1999) and Mickovski and Ennos (2003). Roots <10 mm in diameter were removed from the root systems with secateurs and roots were numbered to aid measurement and data analysis. Measurements were made for all roots in control trees and only where roots had not been cut in test trees. Two types of roots were measured in this study: first order lateral roots (woody roots growing horizontally from the base of the trunk, with a branching angle <45° from the soil surface) and vertical roots (woody roots originating from the underside of lateral roots, with a branching angle >45° from the soil surface). In order to investigate the influence of root system architecture and morphology on root system anchorage, the orientation (azimuth) of each first order lateral root was measured together with horizontal ($d_h$) and vertical ($d_v$) diameters at four different distances of 0.2, 0.5, 1.0 and 1.5 m from the stem base. For vertical roots, these measurements were made at vertical intervals of 0.3 m from the stem base and data grouped into horizontal distance classes from the stem (0.0 – 0.19 m; 0.20 – 0.49 m; 0.50 – 0.99 m and 1.0 – 1.5 m). Root cross-sectional area (*CSA*) was then calculated at each distance from the tree stem (Equation 2):

$$rootCSA = \frac{\pi d_h d_v}{4} \qquad \text{(Equation 2)}$$

The depth and location of each sinker along the first order lateral was also measured. Due to difficulties in excavating all the roots that were broken, damaged or remained in the ground after winching and extraction, therefore it was not possible to measure all roots.

To determine if first order lateral root shape was related to tree anchorage, root eccentricity (*e*) was calculated along with root *CSA*. Each root was considered as an ellipse. Root *e* was calculated using Equation 3 (Mickovski and Ennos 2003):

$$e = \frac{\sqrt{d_1^2 - d_2^2}}{d_1} \qquad \text{(Equation 3)}$$

Where $d_1$ is the largest root diameter and $d_2$ is the smallest. Values of *e* close to zero indicate that the shape of the root is almost circular whilst values closer to 1 indicate an elliptical root shape.

Data analysis

Turning moment and root anchorage rotational stiffness

The turning moment (*TM*) of root anchorage was calculated by assuming that the tree rotated around an axis that was located at the stem base, the bending of the stem during the pulling test was negligible and the stem was initially perfectly vertical. *TM* was defined as the product of the force magnitude (*F*) applied to the tree (assuming that the force is acting at the right angle to the tree stem) and the lever arm (*h*) that was the distance of the cable from the tree rotation axis (Figure 2).

$TM = Fh$ (Equation 4)

The lever arm ($h$) was calculated with regards to the horizontal distance ($D$) in meter between the test and anchoring trees, together with the angle ($\alpha$) between the cable and horizontal directions:

$h = D \sin\alpha$ (Equation 5)

Angle ($\alpha$) between the cable and horizontal directions depended upon the horizontal ($q_x$) and vertical ($q_y$) components of the stem deflection at the point of attachment of the cable:

$$\alpha = \arctan\left[\frac{H - q_y}{D - q_x}\right] \quad \text{(Equation 6)}$$

Expressing these components ($q_x$) and ($q_y$) with regard to the stem deflection angle ($\theta$) and the height of the cable ($H$), and incorporating into Equation 6 gives:

$$\alpha = \arctan\left[\frac{H(1 - \cos\theta)}{D - H\sin\theta}\right] \quad \text{(Equation 7)}$$

*TARS* was then defined as in equation 8:

$$TARS = \frac{TM}{\theta} \quad \text{(Equation 8)}$$

Relative tree anchorage rotational stiffness

*TARS* given by Equation 8 can be used to quantify tree anchorage rigidity before and after trenching. In order to evaluate the change in stiffness after trenching, we defined the Relative value of Anchorage Rotational Stiffness (*RARS*) as

$$RARS = \frac{(TARS_0 - TARS_t)}{TARS_0} \quad \text{(Equation 9)}$$

where ($TARS_0$) was the (*TARS*) calculated at a stem deflection angle of $\theta = 10°$ before trenching, and ($TARS_t$) the *TARS* calculated at the same stem deflection after trenching. *RARS* was expected to be a positive percentage, i.e. $TARS_t < TARS_0$, and was thus considered as an indicator of the stiffness loss after cutting.

Critical turning moment

The $TM_{crit}$ was defined by incorporating Equations 4, 5, and 7 together with the maximum force ($F_{max}$) recorded during the winching tests when the tree was winched until failure, at the corresponding deflection angle ($\phi_{max}$).

$$TM_{crit} = F_{\max} D \sin\left[\arctan\left(\frac{H \cos \theta_{\max}}{\left(D - H \sin \theta_{\max}\right)}\right)\right] \quad \text{(Equation 10)}$$

Root system morphology

For statistical analysis, each root system was divided into twelve 30° radial sectors with regard to the winching direction i.e. CW was considered to be at 0°. First order lateral root number, mean and the sum (Σ) of root *CSA* were calculated within each sector, at a distance of 0.2 m from the stem. The ratio between first order lateral root *CSA* and root number was also determined in each sector using root number divided by root *CSA*. To determine whether slope angle influences root system distribution, each root system was also divided into two 90° radial sectors with regard to slope position (upslope = 0°). This type of analysis allows any preferential directions of root growth to be investigated, and when combined with winching data, can show which part of the root system contributes most to anchorage (Sommerville 1979, Stokes et al. 1995, Nicoll et al. 2006).

Statistical analysis

One-way analysis of variance (ANOVA) and Fisher Least Significant Difference (LSD) tests were used to determine if differences in $TM_{crit}$, TARS and root morphological data existed between groups of trees and if differences in soil moisture content occurred with depth and soil BD with site location existed. If trees had been trenched at e.g. 1.5 m, root characteristics were missing at this distance and these trees were excluded from the analysis of root morphology at 1.5 m. Mean first order lateral root orientation was calculated using circular statistics and Rao's spacing test used to check the null hypothesis that the data were uniformly distributed (Batschelet 1981, Mardia and Jupp 2000, Oriana © 1994-2003 Kovach Computing Services). Normality of data for each treatment was tested using an Anderson-Darling test (data were normally distributed when $P > 0.05$, Appendix 1). To examine the directional allocation of root biomass, the centre of mass of all the first order lateral roots, defined as the mean position of the root mass within the root system relative to the stem centre, was calculated using azimuth angles and weighted by *CSA* (Nicoll et al. 1995, Chiatante et al. 2003, Mickovski and Ennos 2003). The origin of the coordinate system is the centre of the tree trunk, and if the centre of the root *CSA* is at the origin, root mass is considered evenly distributed around the tree stem. The greater this distance (or mean vector, *r*), the more the roots tend to cluster in a preferred direction. Data presented are means ± standard error.

Stepwise regression analysis was carried out between $TM_{crit}$, TARS and individual or combined tree morphological characteristics to determine which parameters were the best predictors of root anchorage. Combined predictors have been shown to be better indicators of pull-out resistance than single predictors (Bailey et al. 2002, Dupuy et al. 2005a, Khuder et al. 2007). The predictors used included $DBH^2$, $DBH^3$, $DBH^4$ and $DBH^2$ x height as these have been shown to be good predictors of $TM_{crit}$ (Cucchi et al. 2004, Nicoll et al. 2006), as well as relative root depth (root depth/total root depth), root plate size, lateral root number, root CSA and eccentricity. These regressions were performed for data at different trenching distances from the trunk.

The relationship between Σ root CSA, number of first order lateral roots and the ratio between first order lateral root number and root *CSA* in each of the twelve 30° radial sectors with TARS before cutting, was explored using Pearson's correlations, considering all trees together.

Results

Effect of trenching on anchorage

Failure through uprooting of the root system occurred in 25 trees, whereas three trees broke at the stem-root base. Mean $TM_{crit}$ for all trees, regardless of trenching treatment was 37.1 ± 2.6 kNm. A decrease in $TM_{crit}$ occurred as trenching occurred closer to the trunk, but variability was high, therefore $TM_{crit}$ did not differ significantly between groups of trees (Table 2.2). Root plate depth and diameter did not differ significantly between groups of trees (Table 2.3).

Table 2.2. Critical turning moment ($TM_{crit}$) and relative anchorage rotational stiffness (RARS) before and after cutting in all trees (data are means ± standard error). Where letters in superscript differ, $P < 0.05$.

| Parameter measured | Trenching distance from stem (m) | | | |
|---|---|---|---|---|
| | 0.5 | 1.0 | 1.5 | control |
| *TMcrit* (kNm) | $32.8 \pm 3.6^{a}$ | $38.6 \pm 3.1^{a}$ | $41.7 \pm 8.7^{a}$ | $36.0 \pm 3.6^{a}$ |
| RARS (%) | $13 \pm 3^{a}$ | $6 \pm 1^{b}$ | $9 \pm 2^{b}$ | - |

Effect of trenching on tree anchorage rotational stiffness

The loss of TARS was low in all treatments, ranging from 6 – 13% after trenching (Table 2.2). RARS was significantly greater when trenching was carried out at a distance of 0.5 m from the trunk compared to distances of 1.0 and 1.5 m (Table 2.2, $F_{3,24} = 5.17$, $P < 0.001$). No significant differences in RARS occurred between trenching distances of 1.0 and 1.5 m.

Soil measurements

Mean soil BD was 1.47 ± 0.01 $gcm^{-3}$ and did not differ significantly within the *E. grandis* stand. Soil moisture content did not differ significantly either between trees or with depth, with mean values of 35.0 ± 1.2% at 0.05 m depth, 36.2 ± 1.6% at 0.30 m depth, and 35.3 ± 1.7% at 0.7 m depth. Therefore, differences in soil physical properties throughout the site were not considered to influence tree anchorage.

Root system morphology

Although variability in root system morphology was high, a general shape could be observed in the uprooted trees (Figure 2.5). Large lateral roots emerged from the stem base and sinker roots descended vertically from the lateral roots and beneath the tree trunk. No taproots were found in these trees. First order lateral root number at the stem base was 26.0 ± 1.4 and this number decreased to only 3.0 ± 0.4 at a distance of 1.5 m, equivalent to a decrease of 88% (Table 2.3). Most of the first order lateral roots (97%) were found at a depth < 0.3 m beneath the soil surface and only 3% were found at a depth of 0.3 – 0.6 m. Mean rooting depth for all trees was 0.7 ± 0.3 m, with sinker roots usually located beneath or close to the stem base. The maximum horizontal spread of most major first order lateral roots was 1.5 m from the trunk, with few roots growing beyond this limit. The lateral root ratio with regard to total root number was 0.62.

a).

b).

Figure 2.5a,b). Excavated root systems of two 20-year old *Eugenia grandis* Wight trees. The root system architecture and morphology of 20-year old *Eugenia grandis* Wight tree grown in the study area.

For sinker roots, the total number per root system ranged from 4 to 31, with a mean of only 17 roots per tree. Of all the trees studied, sinker roots were missing from two root systems, hence these systems were relatively shallow (maximal depths of 0.3 and 0.4 m). 88% of the total sinker roots occurred within a distance < 0.5 m from the stem base, and 32% of these roots were located at the stem base. The maximum depth of these sinker roots located close to the stem was 0.81 ± 0.09 m. Mean sinker root size, mean sinker CSA and rooting depth decreased significantly with distance along the horizontal roots (Table 2.3). No significant relationship existed between the mean total number of sinker roots and any stem size variable.

The mean CSA of first order lateral roots decreased significantly from 170.0 ± 10.6 mm² at a distance of 0.2 m from the trunk to 44.8 ± 7.7 mm² at 1.5 m from the stem ($F_{3,98}$ = 46.6, P < 0.001, Table 2.3). The mean total CSA of all first order lateral roots also decreased significantly with distance (Table 2.3, $F_{3,98}$ = 150.77, P < 0.001), with the highest value of (4723 ± 233 $mm^2$) at a distance of 0.2 m from the stem base. Mean total root CSA at 0.2 m from the stem regressed significantly with DBH, although $R^2$ was low ($y = 34.6x - 474$, $R^2 = 0.26$, $P < 0.01$). However, no significant relationships were found between mean total root CSA and any other root or shoot variable. When mean stem CSA was regressed against total root CSA, a significant positive relationship was found, although $R^2$ was low ($y = 0.152x + 2312$, $R^2 = 0.36$, $P < 0.001$).

Table 2.3. General characteristics of major structural roots (diameter >10 mm) of *Eugenia grandis* Wight in the study area by distance class: a). lateral roots, and b). sinker roots (data are means ± standard error). Where letters in superscript differ, $P < 0.05$.

| Parameter measured | Distance class from stem (m) | | | |
|---|---|---|---|---|
| a). Lateral roots | 0.2 | 0.5 | 1.0 | 1.5 |
| No of roots | 26.0 ± 1.4$^a$ | 22.0 ± 1.6$^b$ | 8.0 ± 1.1$^c$ | 3.0 ± 0.4$^c$ |
| Mean *CSA* (mm²) | 170.0 ± 10.6$^a$ | 92.2 ± 7.7$^b$ | 52.3 ± 5.9$^c$ | 44.8 ± 7.7$^c$ |
| Mean total *CSA* (mm²) | 4723 ± 233$^a$ | 1973 ± 184$^b$ | 427 ± 66$^c$ | 117.8 ± 19.2$^c$ |
| Mean eccentricity (*e*) | 0.7 ± 0.02$^a$ | 0.5 ± 0.02$^b$ | 0.4 ± 0.02$^c$ | ND |
| Root plate diameter (m) | - | 2.08 ± 1.60$^a$ | 2.47 ± 0.29$^a$ | 2.01 ± 0.18$^a$ |
| | Distance class from stem (m) | | | |
| b). Sinker roots | 0.0 – 0.19 | 0.20 – 0.49 | 0.50 – 0.99 | 1.0 – 1.5 |
| Maximum depth (m) | 0.70 ± 0.02$^a$ | 0.80 ± 0.03$^b$ | 0.70 ± 0.05$^a$ | ND |
| Mean no of sinker roots | 8.0 ± 0.8$^a$ | 7.1 ± 0.8$^b$ | 3.7 ± 0.8$^c$ | 1.5 ± 0.5$^c$ |
| Mean *CSA* (mm²) | 73.2 ± 6.9$^a$ | 59.1 ± 7.7$^a$ | 55.3 ± 16.5$^a$ | ND |
| Mean total *CSA* (mm²) | 636.8 ± 73.6$^a$ | 400.8 ± 47.2$^b$ | 203.3 ± 52.5$^c$ | ND |

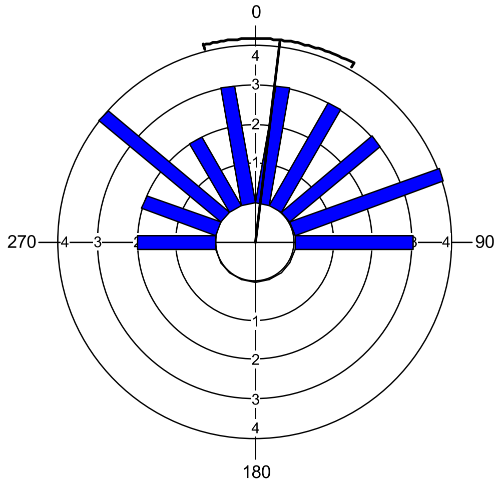
ND = not enough data available

Lateral root directional analysis

Mean azimuth when all first order lateral roots were considered together was 7.0 ± 11.9° and these roots were significantly clustered in this direction, but with a bimodal distribution towards the NE and

NW ($r = 0.6$, Rao's spacing test: $P < 0.01$, Figure 2.6a). When root CSA was taken into consideration, the centre of root mass shifted slightly to a mean azimuth of 16.3° ± 10.3 ($r = 0.64$, Rao's spacing test: $P < 0.01$) indicating significant clustering of the root system, (Figure 2.6b), with mean root CSA clustered towards the NE.

a).




b).

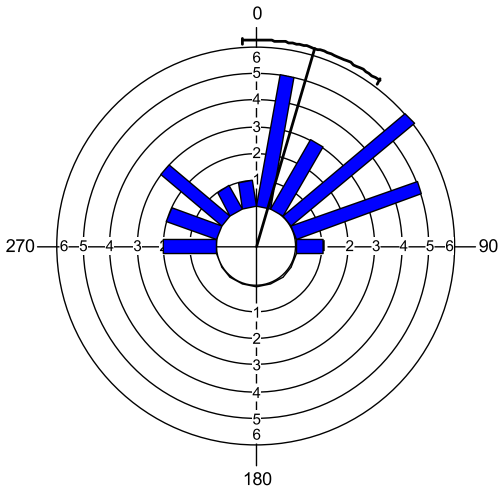



Figure 2.6a). Significant clustering of first order lateral roots towards an angle of 7.0 ± 11.9° (solid line) occurred when the mean azimuth was calculated with regard to north (where winching direction = 0°). b). When first order lateral root CSA for all trees with regard to winching direction was determined, significant clustering of first order lateral roots occurred towards an angle of 16.3 ± 10.3°. Each bar indicates the mean orientation of first order lateral roots for each tree and the solid line indicates the direction of clustering of center of CSA for all trees.

Root eccentricity

Root vertical *e* decreased significantly with distance from the tree trunk (Table 2.3, $F_{2,81} = 43.5$, $P < 0.01$), with the highest value of 0.7 ± 0.02 at a distance of 0.2 m from the stem base, indicating that these roots had adopted elliptical form. However, at a distance of 0.5 and 1.0 m from the trunk, roots were significantly more circular in shape (Table 2.3) as compared to roots at 0.2 m from trunk. No significant relationships were found between root *e* and any other tree parameter.

Relationship between root system anchorage and morphology

When $TM_{crit}$ was regressed against various root and shoot morphological characteristics for control trees, highly significant relationships were found with stem DBH, $DBH^2$, $DBH^3$, and rooting depth (Table 2.4). For trees where roots had been cut at 1.5 m, RARS best regressed with rooting depth and a combination of predictors of tree height, root plate diameter and rooting depth (Table 2.4). Surprisingly, no significant relationships existed between any variable and RARS in trees where roots had been cut at 1.0 m. In trees where roots had been cut at a distance of 0.5 m from the stem, DBH parameters best regressed with RARS, although $R^2$ was not high ($R^2 = 0.58$, Table 2.4). No significant relationships existed with any other shoot or root variable.

Table 2.4. Linear regressions between $TM_{crit}$ or tree anchorage rotational stiffness (TARS) and various tree physical parameters at different distances from the tree trunk (in order of decreasing $R^2$).

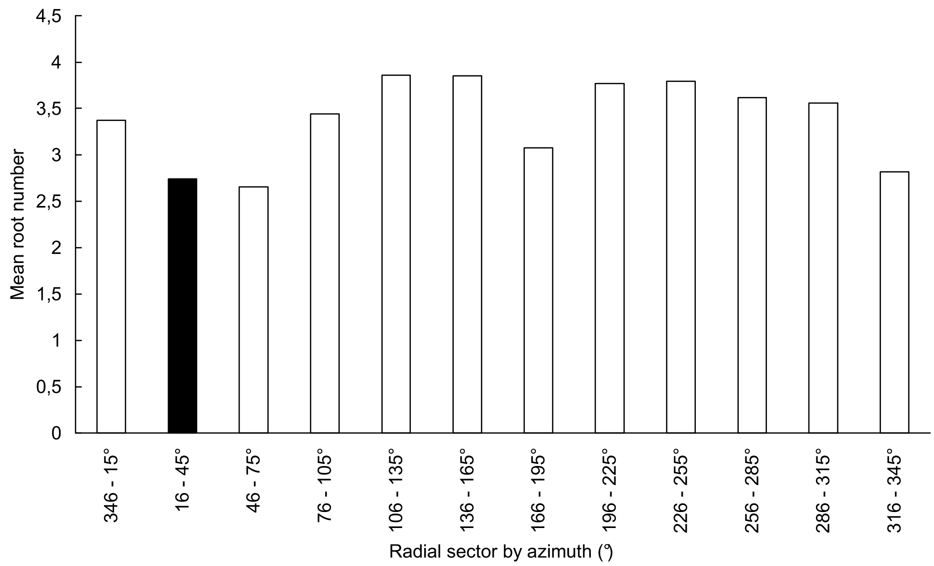
| Regression equation | $R^2$ | P |
|---|---|---|
| Control trees | | |
| $TM_{crit}$ = - 19.4 + 3.97 DBH - 1.55 Height | 0.99 | < 0.001 |
| $TM_{crit}$ = - 29.7 + 2.97 DBH + 0.148 Max. Root Depth | 0.99 | < 0.001 |
| $TM_{crit}$ = - 25.0 + 2.72 DBH + 348 Rel. Max. Root Depth | 0.99 | < 0.001 |
| $TM_{crit}$ = - 39.8 + 3.58 Height + 1080 Rel. Max. Root Depth | 0.99 | 0.001 |
| $TM_{crit}$ = - 41.8 + 4.83 DBH - 0.656 NL | 0.99 | 0.002 |
| $TM_{crit}$ = - 41.8 + 4.83 DBH - 0.656 NL | 0.99 | 0.002 |
| $TM_{crit}$ = - 1.22 + 0.408 Root Depth + 7.61 Root Plate Diameter | 0.98 | 0.002 |
| $TM_{crit}$ = - 5.67 + 662 Rel. Max. Root Depth + 1.07 NL | 0.98 | 0.003 |
| $TM_{crit}$ = - 40.8 + 4.11 DBH - 1.50 Root Plate Diameter | 0.98 | 0.003 |
| $TM_{crit}$ = 38.5 DBH - 38.8 | 0.98 | < 0.001 |
| $TM_{crit}$ = 0.103 $DBH^2$ - 3.41 | 0.97 | < 0.001 |
| $TM_{crit}$ = 0.00365 $DBH^3$ - 8.42 | 0.97 | < 0.001 |
| $TM_{crit}$ = - 11.4 + 0.319 Max. Root Depth + 1.22 NL | 0.97 | 0.006 |
| $TM_{crit}$ = - 42.8 + 3.43 Height + 0.553 Max. Root Depth | 0.93 | 0.017 |
| $TM_{crit}$ = 1015 Rel. Max. Root Depth +12.3 | 0.90 | 0.004 |
| $TM_{crit}$ = 1.84 + 0.00633 Height x $DBH^2$ | 0.87 | 0.007 |
| $TM_{crit}$ = 0.521 Max. Root Depth + 7.32 | 0.85 | 0.009 |
| $TM_{crit}$ = - 18.3 + 2.22 NL | 0.82 | 0.014 |
| Trees with roots cut at 1.5 m distance from the stem | | |
| $TM_{crit}$ = - 11.7 + 0.759 Max. Root Depth - 4.73 Root Plate Diameter | 0.99 | 0.007 |
| $TM_{crit}$ = - 11.0 - 2.54 Height + 37.6 Root Plate Diameter | 0.97 | 0.034 |

| | | |
|---|---|---|
| $TM_{crit}$ = - 64.1 + 1.41 DBH + 32.5 Root Plate Diameter | 0.94 | 0.034 |
| $TM_{crit}$ = - 35.0 + 0.0121 Height x DBH² | 0.61 | 0.039 |
| TARS = 0.0673 + 0.00760 Max. Root Depth - 0.243 Root Plate Diameter | 0.98 | 0.025 |
| TARS = 0.048 - 0.0118 Height + 0.00306 Max. Root Depth | 0.86 | 0.019 |
| TARS = 0.174 - 0.0199 Height + 5.69 Rel. Max. Root Depth | 0.83 | 0.030 |
| TARS = - 0.188 + 0.00390 DBH + 0.00292 Max. Root Depth | 0.81 | 0.037 |
| TARS = 0.00286 Max. Root Depth - 0.101 | 0.79 | 0.008 |
| TARS = - 0.0949 -0.000057 Mean CSA 0.2 + 0.00291 Root depth | 0.79 | 0.044 |
| TARS = 4.58 Rel. Root Depth - 0.0647 | 0.64 | 0.031 |
| Trees with roots cut at 1.0 m distance from the stem | | |
| *No significant relationships* | | |
| Trees with roots cut at 0.5 m distance from the stem | | |
| TARS = - 0.147 +0.000045 Height x DBH² | 0.53 | 0.041 |
| TARS = 0.000019 DBH³ - 0.00498 | 0.56 | 0.032 |
| TARS = 0.000619 DBH² - 0.147 | 0.55 | 0.036 |
| TARS =0.0270 DBH - 0.438 | 0.53 | 0.040 |

NL = No of lateral roots

No significant correlations were found between Σ root *CSA* in each of the twelve 30° radial sectors and TARS before cutting. However, root number was negatively correlated with TARS in one sector only: 16 - 45°, i.e. on the CW side of the tree (R = -0.43, P = 0.030, Figure 2.7a). A negative correlation also existed between TARS and the ratio of lateral with root number with *CSA* in the CW sector 346 – 15° (R = -0.38, P = 0.05, Figure 2.7b) and the WW sector 106 - 135° (R = -0.47, P = 0.014, Figure 2.7b).

a)




b)

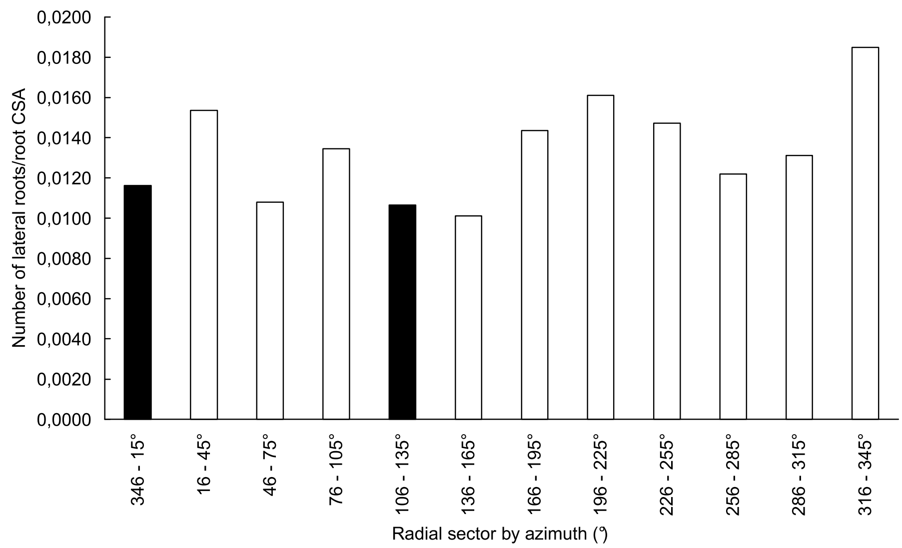



Figure 2.7. Relationship between a) mean root number and b) ratio between first order lateral root number and CSA with bending stiffness before cutting in each of the twelve 30° radial sectors. The counter-winchward direction was considered to be at 0°. Black bars indicate sectors where Pearson's correlations were significant ($P < 0.05$).

Discussion

The effect of trenching on TARS was slight, with a loss of only 13% when roots were cut at a distance of 0.5 m from the tree trunk and surprisingly, no significant differences in $TM_{crit}$ were observed with regard to trenching distance from the tree stem, possibly due to the variability observed in the data. Root system architecture was highly asymmetric, and the direction of winching and trenching was random. If we had winched trees along e.g. the direction of most growth or the prevailing wind direction, as suggested by Stokes (1999) and Cucchi et al. (2004), we may have observed more striking results with regard to trenching. Nevertheless, although trenching appeared to have little direct influence on tree mechanical stability, by analysing the relationships between $TM_{crit}$ or TARS and tree morphological characteristics, we were able to determine several mechanisms involved in root anchorage.

The relationship between root anchorage and various shoot and root parameters have often been used to determine which are the best characteristics to predict uprooting resistance in trees (Dupuy et al. 2005a, 2007, Nicoll et al. 2006, Peltola 2006, Khuder et al. 2007). We found many significant regressions between $TM_{crit}$ and TARS and different variables in the control group of trees, but the most significant relationships were with a combination of the parameters DBH or tree height and root system depth. As most sinker roots were located close to the trunk, these roots would not be damaged through trenching, and could therefore continue to function as major component of anchorage (Mickovski and Ennos 2003), even though the amount of biomass allocated to these roots was significantly less than that in the lateral roots (Table 2.3). Fourcaud et al. (2008) also showed through numerical modelling of tree anchorage in a saturated clay soil, that if a taproot is present, the length ratio of this taproot with the length of the zone of rapid taper (ZRT) is also an important component of anchorage. The ZRT is the zone of major growth in lateral roots adjacent to the stem base (Wilson 1975) and tapers quickly so that eccentrically shaped roots rapidly become more circular. In trees in our study, sinker roots were clustered together underneath the tree stem, therefore could be considered as acting like a single, large taproot which act as the dominant component of anchorage. If the length ratio between this taproot and the length of the ZRT is > 1, Fourcaud et al. (2008) suggest that the taproot is the dominant component of anchorage, therefore, trenching lateral roots will have little effect on anchorage. In *E. grandis*, the ZRT could be considered as being shorter than 0.5 m, whereas maximum sinker depth was 0.7 m, also located underneath the trunk.

In trees where trenching had been carried out, root loss during excavation of the root systems may have also influenced the results as no significant relationships between $TM_{crit}$ or TARS and root characteristics were found. However, when trenching was carried out at distances of 0.5 or 1.0 m from the tree stem, no significant relationships were found between $TM_{crit}$ and any other parameter, nor were any relationships found between TARS and any root system variable, including depth. When trenching was performed at a distance of 1.5 m from the trunk, a combination of the parameters root system depth and root plate diameter or tree height were the best predictors of both $TM_{crit}$ and TARS and several significant relationships were found between TARS and DBH, tree height and root system width and depth. Therefore, when roots were cut through trenching at distances of less than 1.5 m, something happened to the anchorage mechanism which prevents uprooting resistance being predicted from root system parameters. In our study, we could not know if the longest lateral roots were cut, as trenching would have damaged these roots which were left in the soil, but it would seem likely that this could have been the case.

It was surprising that no significant regressions were found between root CSA and $TM_{crit}$ or TARS, even in the control trees, where significant relationships were more numerous. Root CSA has been considered as playing a major role in tree anchorage, particularly in roots close to the stem (Nicoll and Ray 1996, Coutts et al. 2000, Nicoll 2000, Chiatante et al. 2003, Danjon et al. 2005). Nevertheless, significant negative correlations were found between TARS before trenching and the number of first order lateral roots in the CW sector at 16 – 45° and the ratio between first order lateral root number and CSA in the neighbouring sector (346 – 15°) and opposite sector of WW (106 - 135°). No relationship occurred between TARS and root *CSA* in any sector, but significant result was found between TARS and the ratio of number of lateral roots and root *CSA*, which suggests that an increase in root *CSA* on the CW side (side held in tension) of the tree may increases anchorage, however at the expense of lateral root number. These results are contrary to those found by Coutts (1983), who showed that the thickness of lateral roots on the WW side (side held in compression) of the tree will influence positively anchorage rigidity, whereas on the CW side, an increase in root number will augment overturning resistance (Stokes et al. 1995).

When all the azimuths of all first order lateral roots were analysed, it was found that lateral roots were significantly clustered with a bimodal distribution towards the NE and NW. However, when the centre of mass of all first order lateral roots was calculated, using azimuth angles and weighted by *CSA*, the mean azimuth towards which roots were clustered was slightly shifted towards 16.0°. This clustering of lateral roots did not affect anchorage, as found by Mickovski and Ennos (2003) studying *Pinus peuce* Griseb. In our study, both sets of results indicate that there is an increased allocation of root biomass on the northern side of the tree. Asymmetric structural root growth in temperate trees is related to genotype (Nicoll et al. 1995), competition between roots for nutrients early on in their development (Coutts, 1987), poor planting conditions (Taylor and Gardner 1963, Coutts et al. 2000, Lindström and Rune 1999) and mechanical loading e.g. unilateral wind loading (Stokes et al. 1995, Mickovski and Ennos 2003,) or slope orientation (Watson et al. 1995, Chiatante et al. 2003, Di Iorio et al. 2005, Nicoll et al. 2006). Radial growth of roots is also influenced by mechanical stresses, which are usually higher at the base of the tree, thus resulting in thicker roots in this zone (Nicoll and Ray 1996). Our results suggest therefore that the asymmetric root systems in *E. grandis* trees may in part be due to the mechanical loading from the northerly prevailing wind direction during the monsoon season. However, the trees were also growing on a slight slope of 7 - 10° and preferential root clustering corresponded to the upslope direction. Therefore, the combination of dynamic and static stresses, which has already been shown to result in amplified plant response to mechanical loading (Berthier and Stokes 2006, Khuder et al. 2006), may have augmented root growth on the northern side of the tree. The results of our study are comparable to those of Nicoll et al. (2006) who examined root system symmetry of 40 year old Sitka spruce (*Picea sitchensis* Bong. Carr.) grown on a steep slope (26-33°), where roots were distributed unevenly around the trunk, growing predominantly up and across the slope in windward direction.

Not only does mechanical stress lead to an increase in root radial growth, but also contributes towards eccentric secondary growth (Nicoll and Ray 1996, Stokes et al. 1998, Mickovski and Ennos 2003). Root *e* was highest close to the trunk in the *E. grandis* trees studied, with most growth along the vertical bending axis. However, at a distance of 0.5 m and 1.0 m from the stem, root eccentricity was significantly less elliptical, and more significantly circular in shape. Radial eccentricity has been linked to the distribution of strain throughout the root system during mechanical loading (Ennos 1993, Nicoll and Ray 1996, Fourcaud et al. 2008). Roots often have greater thickening on the upper sides where strain is high, producing a shape comparable to a “T-beam” close to the trunk on leeward side of the tree or “I-beam” shapes further away from the trunk, particularly on the windward side where roots experience tension and bending (Nicoll and Ray 1996, Mickovski and Ennos 2003, Di Iorio et al. 2007). Such changes in root *CSA* can resist bending resistance within the soil more than any other shape with a similar *CSA* (Nicoll 2000) and further increase rigidity of the root soil plate (Nicoll and Ray 1996).

Our study showed that in terms of TARS and $TM_{crit}$, tree mechanical stability was not greatly affected by trenching in *E. grandis* trees, even when roots were severed at 0.5 m from the trunk. As maximal rooting depth was a good predictor of anchorage and most sinkers were located close to the trunk, the severing of lateral roots probably had little effect on tree stability, even though the amount of biomass allocated to lateral roots was significantly greater than that in the sinker roots. However, the fundamental root anchorage mechanism was disrupted in that overturning resistance could not easily be predicted from root system characteristics when trenching occurred at 0.5 or 1.0 m. Fourcaud et al. (2008) suggest that in clay soils, the longest lateral roots determine the size of the soil-root plate, a major component of tree anchorage, therefore this plate should not be damaged. However, the same authors also show that the ratio between taproot length (or central sinkers) and the ZRT is a dominant component of tree anchorage. Hence, it is difficult to give advice to the arborist concerning the minimal distance to be left between the stem and the trench, as this will differ depending on species, soil conditions and tree vigour. From our study, we suggest that rooting depth and root plate size are important criteria to consider before trenching is carried out. Root plate radius is correlated to stem radius and this simple relationship can therefore be adapted to many species in different environments (Mattheck and Breloer 1995). Nevertheless, the effect of trenching may not be perceived immediately, and there is also a high risk of pathogens entering the severed roots and causing decay in the tree, thus decreasing mechanical stability further. Further similar studies still need to be carried out on different species in a variety of urban conditions, in order to elucidate further the effect of root loss on trees growing in the built-up environment.

# CHAPTER 3: THE EFFECT OF ROOT ARCHITECTURE AND ROOT LOSS THROUGH TRENCHING ON THE ANCHORAGE AND STABILITY OF TAPROOTED *Pinus pinaster* Ait

Abstract

The effect of root cutting through trenching was investigated on the biomechanics of mature *Pinus pinaster* Ait. Each tree was winched sideways to 0.2 m from the vertical, released and trenched at three different distances from the trunk. The first trench was made at a distance of 1.5 m, the tree pulled again and released; the second trench was cut at 1.0 and the same procedure carried out. The final trench was at 0.5 m from the trunk and trees were then pulled until failure. The force necessary to winch trees 0.2 m from the vertical was measured. Trenches were dug on the windward (WW) side of trees. No trenches were made in a control group of trees which were winched until failure occurred. Critical turning moment ($TM_{crit}$) and tree anchorage rotational stiffness (TARS) before and after trenching were calculated. Root systems extracted for architectural analysis and relationships between architectural parameters and $TM_{crit}$ and TARS were investigated.

No differences were found between $TM_{crit}$ with trenching distance but TARS decreased significantly when roots were cut at 0.5 and 1.0 m from trunk. In trees where roots were cut at 1.5 and 1.0 m, significant regressions were found between TARS and both single as well as combination of parameters e.g. tree dimension (DBH and tree height), relative and total root depth, taproot length, taproot diameter and no of sinker roots. When trenching was performed at 1.0 m, significant relationships were found between $TM_{crit}$ and combination of parameters such as root cross-sectional area (CSA), relative and total root depth, taproot length and diameter and tree dimension. Meanwhile, when trenching was carried out at 0.5 m, a significant relationship only existed between $TM_{crit}$ and a combination of root CSA and relative root depth. Our study showed that in terms of TARS and $TM_{crit}$, mechanical stability was significantly affected by trenching at a distance of 1.0 and 0.5 m from the stem, probably due to the severing of lateral roots that greatly altered the size of root plate which subsequently root CSA of major lateral roots and number of sinkers, which are crucial components in anchorage and stability of mature *P. pinaster* trees grown on sandy soil.

Key words: biomechanics, anchorage rotational stiffness, critical turning moment, mechanical stability, acclimation, root eccentricity.

Introduction

Maritime pine (*Pinus pinaster* Ait.) is a conifer species predominant in the Aquitaine region, south-west, France. It covers an area of over 890,000 ha and makes up 7% of total French forest area (Cucchi et al. 2004) making it one of the most important trees in the forest industry in France. The trees were planted widely across the landscape of south-west of France due to its economic as well as its ecological importance. Due to several catastrophic and devastating wind storms that hit Europe in recent years (Cucchi and Bert 2003), research into root architecture (Danjon et al. 1999, Danjon et al. 2005) and anchorage (Stokes 1999, 2000, Cucchi and Bert 2003, Cucchi et al. 2004, Danjon et al. 2005, Dupuy et al. 2005a,b) on this particular forest tree species had increased enormously.

Despite the variability found in the mature root system of *P. pinaster*, it has been characterized as a taproot system (Köstler et al. 1968, Stokes 2002), consisting of a large taproot, vertical sinkers and smaller horizontal and vertical roots. The taproot plays an important role in the stability and anchorage of small and young *P. pinaster* trees (Danjon et al. 1999b, Khuder et al. 2007), whereas older trees need well developed lateral roots in order to resist overturning (Crook and Ennos 1997). The zone of rapid taper (ZRT, Wilson 1975) is the zone of major growth in lateral roots adjacent to the stem base (Wilson 1975) and tapers quickly so that eccentrically shaped roots rapidly become more circular. This ZRT contributes to the rigidity of the entire soil-root plate (Danjon et al. 2005). A greater stiffness and larger soil-root plate thus ensures small displacements sooner during uprooting and may prevent initial failure in the soil (Coutts 1986). Similar findings were also reported by Cucchi et al. (2004) who found that this critical loading point was reached at the beginning of overturning tests on mature *P. pinaster*, when stem inclination was small. These findings suggest that root plate rigidity plays a key role during the early stage of tree failure. Nevertheless, the actual contribution of the taproot, vertical sinkers and lateral roots to anchorage is still not known. Numerical modelling can be carried out to determine the importance of each anchorage component (Fourcaud et al. 2007), but such models still need validating with field data.

In spite of their frequent designation as a deep-rooted species as in the case of many conifer species (Mickovski 2002), pine root system architecture can be modified depending on soil conditions, from taproot type to sinker, superficial and plate root systems (Gruber 1994, Puhe 2003). In the presence of impervious layers in the soil such as a hard pan, the vertical growth of roots is often limited, resulting in the formation of a shallow root system. Danjon et al. (2005) reported that in *P. pinaster* root systems, when the taproot reaches this layer, there is a threshold where an additional biomass allocation to the taproot will not provide any additional contribution to anchorage, although deep vertical roots are crucial in providing anchorage, especially in sandy soil (Dupuy et al. 2005b, Fourcaud et al. 2007).

Although the biomechanics of anchorage in *P. pinaster* has been much elucidated in recent years (Stokes et al. 1998, Stokes 1999, Cucchi et al. 2004, Dupuy et al. 2005a), few studies combine an investigation of root anchorage with architecture (Danjon et al. 2005, Khuder et al. 2007). However, despite acknowledging the important role of primary lateral roots in the stability of large trees, a review on past literature showed no attempt was made to study the effect of root removal on anchorage of mature *P. pinaster*. Through static winching tests, tree behaviour under wind loading can be simulated (Achim et al. 2005, Mickovski and Ennos 2003, Cucchi et al. 2004, Nicoll et al. 2005, Peltola 2006), and together with the information from winching tests and architectural analysis, it is possible to identify those characteristics influencing uprooting the most. A laborious but practical method for investigating the influence of root system characteristics on tree anchorage is to observe the effect of root removal on resistance to overturning during winching tests (Coutts 1983, 1986, Crook et al. 1997). Such a method could be used to determine the effect on anchorage due to root removal through trenching (see Chapter 2). Together with data on root system morphology, the biomechanics of anchorage in *P. pinaster* could be investigated in detail. Although not a species utilized often in urban situations, *P. pinaster* is a useful model species, due to its specific type of root architecture. The effect of trenching on taprooted urban trees is difficult to quantify, due to the lack of available specimens and the high environmental variability, therefore, trenching tests on *P. pinaster* should provide information about the biomechanics of taprooted species, which could then be applied to landscape trees.

This study was carried out in order to investigate on the effect of root removal through trenching in mature *P. pinaster* grown on sandy podzol soil, in south-west France. Through a series of tests where roots were removed and then winched sideways to failure, the influence of root loss on tree anchorage of mature tap-rooted *P. pinaster* was quantified. Root morphology was also analysed and characteristics correlated with anchorage rigidity. Results are discussed with regard to the anchorage mechanisms in taprooted species and how this knowledge can be applied to trees in landscape areas.

## Materials and Methods

### Site details

The study area was located in a plantation at the Forêt de l'Hermitage, region of Aquitaine, 40 km south-west of France (44°44N', 0°46'W, 58 m above sea level at 45 km from Atlantic Ocean). The site was flat and exposed to prevailing winds from the north-west (NW), with a mean windspeed of 3.3 $ms^{-1}$ and maximum speeds reaching 33.0 $ms^{-1}$ (Stokes 1999). The climate of the study area is an oceanic type, often characterized by hot summers and mild winters. Rainfall is spread over all seasons, with the highest precipitation in autumn and winter. The site receives a mean annual rainfall between 700 – 1000 mm and mean temperatures range from 5 - 7°C in January and 19 - 21°C in July and August (Météo France). The soil at the site consists of a medium humid sandy podzol, with a hard pan at a depth of 0.5 - 1.0 m (Danjon 1999a). This hard pan often limits vertical root penetration. The water table fluctuates, and can be found close to the ground level in wet winters, dropping to about 1.5 m in the middle of summer.

### Tree selection and experimental layout

In November 2004, 20 trees were chosen at random from a 33-year old *P. pinaster* growing on monoculture plantation, planted from seed with a spacing of 2 x 4 m (Figure 3.1). The selected trees (Table 3.1) were chosen from inside the stand, with a mean diameter at breast height (DBH) of 0.26 ± 0.07 m, and mean tree height of 19.30 ± 0.34 m (means ± standard error). A complete randomised design (CRD) was used to divide trees into four groups. Each group consisted of five to eight trees and was subjected randomly to three different soil trenching treatments including a control group where no trenching occurred.

Figure 3.1. Showing study area and 33-year old *Pinus pinaster* Ait trees growing in the plantation at the Forêt de l'Hermitage, region of Gironde, south-west of France.

Table 3.1. Tree characteristics and tree winching parameters of trees in the study area (data are means ± standard error). Where letters in superscript differ, $P < 0.05$.

| Parameter measured | Means ± standard error |
|---|---|
| DBH (m) | 0.26 ± 0.067 |
| Tree height (m) | 19.30 ± 0.34 |
| Height of cable attachment (m) | 1.53 ± 0.02 |
| Distance of test tree to anchor tree (m) | 30.65 ± 1.39 |

Tree winching and trenching tests

Tree winching tests were carried out in mid November 2004 in order to determine the effect of root loss through trenching on root system anchorage. The tests were carried out when soil moisture content was high. Higher soil moisture content results in lower soil shear strength (Crook and Ennos 1997) therefore failure through winching is more likely to occur in the root system than in the trunk. To remove the confounding parameter of trunk weight and crown area on anchorage (Coutts 1986) the trunk was cut at a height of 2.0 m above ground level.

The winching tests were similar to those carried out in previous studies (see Chapter 2), using a cable and motorised winch (Hit Trac, Habegger, Switzerland), with maximal strength capacity of 16 kN. The winch was attached to the base of an anchoring tree, connected to the winch cable and a sling which looped around the trunk of the test tree at a height of 1.8 m. A pulley attached between the tree and the winch was used to double the winch capacity. A force transducer capable of measuring force up to 20 kN (type K25H-20kN, Scaime S.A., France) was connected between the sling and the winch cable. Measurements of angle and force were recorded every second using dataloggers (Almemo 2290-8, Ahlborn, Germany). The distance between the test and anchor tree was also measured (Table 3.1).

To quantify the loss of anchorage rigidity through trenching, each tree was winched sideways along the direction of the prevailing wind (NW) before and after trenching, using a similar technique to that described in Chapter 2. Each tree was winched sideways to 10° from the vertical, released and trenched at three different distances from the trunk. A trench (1 m deep and 3.0 m long, extending 1.5 m from each side of the trunk) was dug on the counter-winchward (CW) side of the tree using a trenching machine (Figure 3.2). Trenches were made at random distances from the trunk e.g. in one test the first trench was made at a distance of 1.5 m, the tree pulled again and released; the second trench was cut at 1.0 and the same procedure carried out. The final trench was at 0.5 m from the trunk where the trees were then pulled until failure. In a second test, the first trench would be at a distance of 0.5 m from the trunk, therefore only one trench would be cut before tree failure. The force required to pull the tree during each test was measured. The CW side of the stem was chosen for trenching as roots in this direction are held in tension and contribute the largest resistance to overturning (Coutts 1983, 1986; Crook and Ennos 1996; Stokes 2002). Therefore, root loss on the CW side of the tree should have a greater effect on anchorage rigidity. Trench dimensions were enough to sever all roots on one side of the tree. In control trees, no trenches were dug and trees were winched directly until failure. Once the winching tests were completed, trees were then excavated using a mechanical digger for measurement of root system morphology. Before to the excavation, the stump of the study tree was marked according to the pulling direction and north. A 1.0 m deep trench was dug around the tree to sever the remaining roots and then slowly removed the root system from the soil. Soil was removed from the root systems manually, and all broken roots were collected and tagged for measurements of root morphology.


Figure 3.2. A mechanical trencher used during the trenching tests in France.

Measurements of root system morphology

Using the method described in Chapter 3, root system morphology was measured in order to determine if there was a relationship with tree anchorage rotational stiffness (*TARS*) and the critical turning moment ($TM_{crit}$). The shape, size and orientation of all structural roots (defined as any woody root with a diameter >10 mm) were quantified using techniques similar to those described by Nicoll and Ray (1996), Drexhage and Gruber (1998), Drexhage et al. (1999) and Mickovski and Ennos (2003). Roots <10 mm in diameter were removed from the root systems with secateurs and roots were numbered to ease measurement and data analysis. Measurements were made for all roots in control trees and only where roots had not been cut in test trees. Three types of roots were measured: first order lateral roots (woody roots growing horizontally from the base of the trunk, with a branching angle < 45° from the soil surface); sinker roots (woody roots originating from the underside of lateral roots, with a branching angle > 45° from the soil surface) and taproots (largest woody roots originating from the stump and growing directly beneath it). Roots growing obliquely from the taproot were counted as vertical roots (Coutts 1989). The orientation (azimuth) of each first order lateral root was measured together with horizontal ($d_h$) and vertical ($d_v$) diameters at distances of 0.2, 0.5, 1.0 and 1.5 m from the stem base. For vertical sinker and tap roots, these measurements were made at vertical intervals of 0.3 m from the stem base and data grouped into horizontal distance classes from the stem (0.0 – 0.19 m; 0.20 – 0.49 m; 0.50 – 0.99 m and 1.0 – 1.5 m). Root cross-sectional area (*CSA*) was then calculated at each distance from the tree stem using above parameters (Equation 1):

$$rootCSA = \frac{\pi d_h d_v}{4} \qquad \text{(Equation 1)}$$

The depth and location of each tap and sinker root along the first order lateral root was also measured. Due to difficulties in excavating all the roots that were broken, damaged or remained in the ground after winching and extraction, it was not possible to measure all roots.

To determine if first order lateral root shape was related to tree anchorage, root eccentricity ($e$) was calculated along with root *CSA*. Each root was considered as an ellipse. Root $e$ was calculated using Equation 2 (Mickovski and Ennos 2003):

$$e = \frac{\sqrt{d_1^2 - d_2^2}}{d_1} \qquad \text{(Equation 2)}$$

Where $d_1$ is the largest root diameter and $d_2$ is the smallest. Values of $e$ close to zero indicate that the shape of the root is almost circular whilst values closer to 1 indicate an elliptical root shape.

Data analysis

Turning moment and root anchorage rotational stiffness

The turning moment (*TM*) of root anchorage was calculated by assuming that the tree rotated around an axis that was located at the stem base, the bending of the stem during the pulling test was negligible and the stem was initially perfectly vertical (see Chapter 2, Figure 2.2). (*TM*) was defined as the product of the force magnitude (*F*) applied to the tree and the lever arm (*h*) that was the distance of the cable from the tree rotation axis.

$$TM = Fh \qquad \text{(Equation 3)}$$

The lever arm (*h*) was calculated with regards to the horizontal distance (*D*) between the test and anchoring trees, together with the angle (α) between the cable and horizontal directions:

$$h = D \sin\alpha \qquad \text{(Equation 4)}$$

Angle ($\alpha$) between the cable and horizontal directions depended upon the horizontal ($q_x$) and vertical ($q_y$) components of the stem deflection at the point of attachment of the cable:

$$\alpha = \arctan\left[\frac{H - q_y}{D - q_x}\right] \qquad \text{(Equation 5)}$$

Expressing these components ($q_x$) and ($q_y$) with regard to the stem deflection angle (θ) and the height of the cable (*H*), and incorporating into Equation 5 gives:

$$\alpha = \arctan\left[\frac{H(1-\cos\theta)}{D - H\sin\theta}\right] \qquad \text{(Equation 6)}$$

*TARS* was then defined as in equation 7:

$$TARS = \frac{TM}{\theta} \qquad \text{(Equation 7)}$$

Relative tree anchorage rotational stiffness

*TARS* given by Equation 7 can be used to quantify tree anchorage rigidity before and after trenching. In order to evaluate the change in stiffness after trenching, we defined the Relative value of Anchorage Rotational Stiffness (*RARS*) as:

$$RARS = \frac{(TARS_0 - TARS_t)}{TARS_0} \qquad \text{(Equation 8)}$$

where ($TARS_0$) was the (*TARS*) calculated at a stem deflection angle of θ = 10° before trenching, and ($TARS_t$) the *TARS* calculated at the same stem deflection after trenching. *RARS* was expected to be a positive percentage, i.e. $TARS_t < TARS_0$, and was thus considered as an indicator of the stiffness loss after cutting.

Critical turning moment

The $TM_{crit}$ was defined by incorporating Equations 3, 4, and 6 together with the maximum force ($F_{max}$) recorded during the winching tests when the tree was winched until failure, at the corresponding deflection angle ($\phi_{max}$).

$$TM_{crit} = F_{max} D \sin\left[\arctan\left(\frac{H(1-\cos\theta_{max})}{D - H\sin\theta_{max}}\right)\right] \qquad \text{(Equation 9)}$$

Root system morphology

For statistical analysis, each root system was divided into twelve 30° radial sectors with regard to the winching direction i.e. CW was considered to be at 0°. First order lateral root number, mean and the sum (Σ) of root *CSA* were calculated within each sector, at a distance of 0.2 m from the stem. The ratio between first order lateral root *CSA* and root number (root number divided by root *CSA*) was also determined in each sector. This type of analysis allows any preferential directions of root growth to be investigated, and when combined with winching data, can show which part of the root system contributes most to anchorage (Somerville 1979, Stokes et al. 1995).

Statistical analysis

One-way analysis of variance (ANOVA) and Fisher Least Significant Difference (LSD) tests were used to determine if differences in $TM_{crit}$, TARS and root morphological data existed between groups of trees. If trees had been trenched at e.g. 1.5 m, root characteristics were missing at this distance and these trees were excluded from the analysis of root morphology at 1.5 m. Mean 1°L root orientation was calculated using circular statistics and Rao's spacing test used to check the null hypothesis that the data were uniformly distributed (Batschelet 1981, Mardia and Jupp 2000, Oriana © 1994-2003 Kovach Computing Services). Normality of data for each treatment was tested using an Anderson-Darling test (data were normally distributed when $P > 0.05$; Appendix 2). In order to examine the directional allocation of root biomass, the centre of mass of all the first order lateral roots, defined as the mean position of the root mass within the root system relative to the stem centre, was calculated using azimuth angles and weighted by *CSA* (Nicoll et al. 1995, Chiatante et al. 2003, Mickovski and Ennos 2003). The origin of the coordinate system is the centre of the tree trunk, and if the centre of the root *CSA* is at the origin, root mass is considered evenly distributed around the tree stem. The greater this distance (or mean vector, *r*), the more the roots tend to cluster in a preferred direction. Data presented are means ± standard error.

To determine which tree parameters were the best predictors of root anchorage, stepwise regression analysis was carried out between $TM_{crit}$, TARS and individual or combined tree morphological characteristics at different trenching distances from the trunk. The predictors used included $DBH^2$, $DBH^3$, $DBH^4$ and $DBH^2$ x height as these have been shown to be good predictors of $TM_{crit}$ (Cucchi et al. 2004, Nicoll et al. 2006, see Chapter 2), as well as relative root depth (root depth/total root depth), number of lateral root, total root depth, depth of sinker, tap root length, root CSA and eccentricity.

In order to determine which part of the root system contributes most to anchorage, the relationship between Σ root CSA, and the ratio between first order lateral root number and root *CSA* in each of the twelve 30° radial sectors with TARS before cutting, was analysed using Pearson's correlations.

Results

Effect of trenching on anchorage

Failure through uprooting of the root system occurred in 18 trees, whereas 2 trees broke at the stem-root base, with mean $TM_{crit}$ of 35.6 ± 1.8 kNm for all trees, regardless of trenching distance. A decrease in $TM_{crit}$ occurred as trenching was done closer to the trunk, but variability was high, therefore $TM_{crit}$ did not differ significantly between groups of trees (Figure 3.3). However, significant differences were found between control and trenched trees.

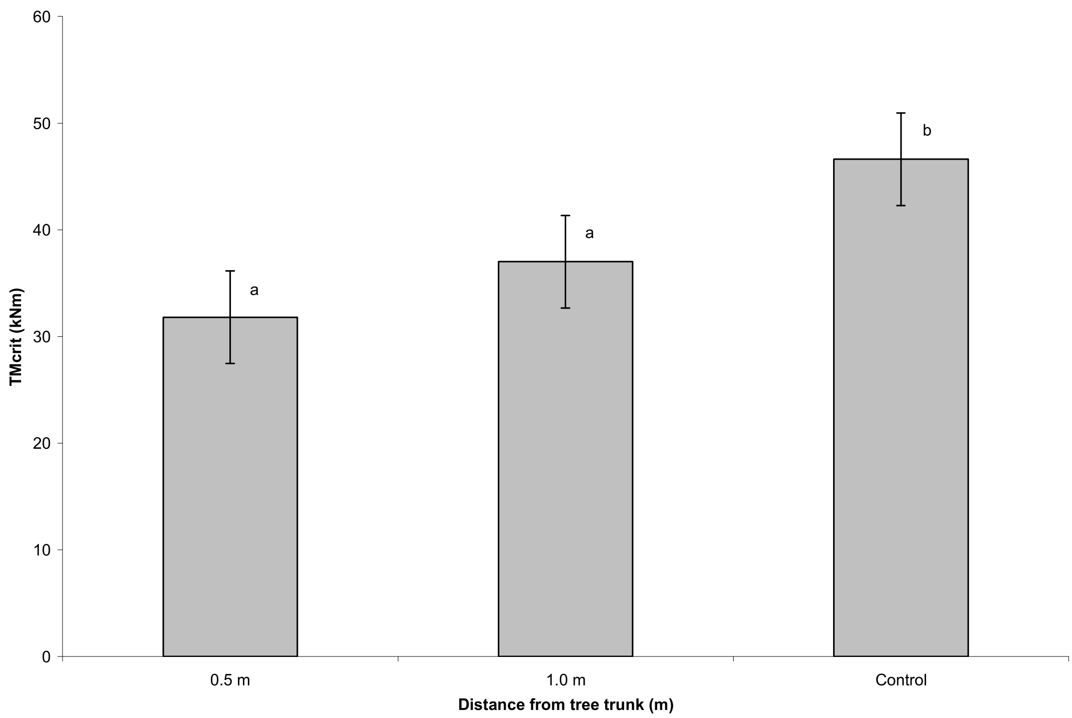



Figure 3.3. Critical turning moment ($TM_{crit}$) of all trees in relation to distance from the tree trunk. The bars are means with standard error. Where letters in superscript differ, $P < 0.05$.

Effect of trenching on relative anchorage rotational stiffness

RARS in all treatments ranged from 8.6 – 29.7%, with significant differences found when trenching occurred at a distance of 0.5 m ($F_{2, 42} = 8.2$, $P < 0.01$, Figure 3.4). A decrease in RARS also occurred as trenching was performed closer to the trunk.

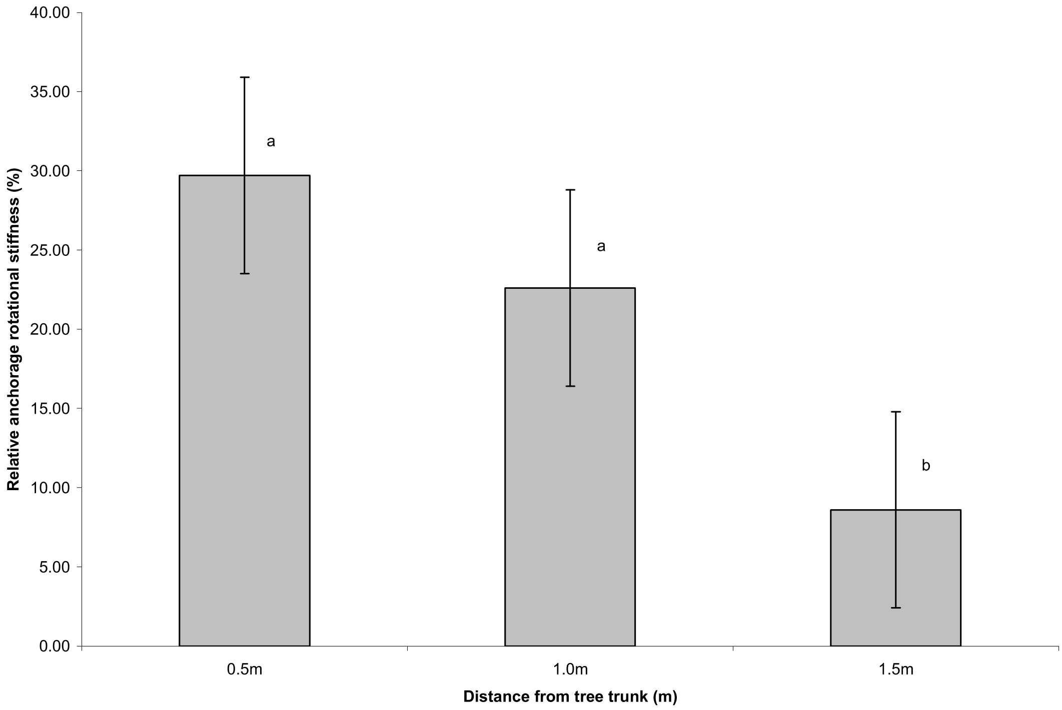



Figure 3.4. Relative anchorage rotational stiffness (RARS) before and after cutting in all trees at different radial distances from tree trunk (The bars are means with standard error). Where letters in superscript differ, $P < 0.05$.

Root system morphology

Despite the high variability found in root system morphology, the general root shape of *P. pinaster* could be observed and characterized as a taproot system (Figure 3.5). Large taproot and lateral roots emerged from the stem base and sinker roots descended vertically from the lateral roots and beneath the tree trunk. First order lateral root number at the stem base was 12.3 ± 0.7 and this number decreased to only 2.7 ± 0.3 at a distance of 1.5 m, equivalent to a decrease of 78% (Table 3.2). Most of the first order lateral roots (91%) were found at a depth < 0.3 m beneath the soil surface, meanwhile only 8% were found at a depth more than 0.3 m. Mean rooting depth for all trees was 1.15 ± 0.05 m, with tap and sinker roots usually located beneath or close to the stem base. The maximum horizontal spread of most major first order lateral roots was around 1.5 m from the trunk, with few roots growing beyond this limit.

Figure 3.5. Root system of a 33-year old *Pinus pinaster* tree grown in a plantation at the Forêt de l'Hermitage, region of Aquitaine, south-west of France.

For sinker roots, the total number per root system ranged from 2 to 20, with a mean of only 9 roots per tree. Of all the trees studied, sinker roots were missing from two root systems, hence these systems were relatively shallow (maximal depths of 0.3 and 0.4 m). 84% of the total sinker roots occurred within a distance < 0.5 m from the stem base, and 36% of these roots were located at the stem base. The maximum depth of these sinker roots located close to the stem was 0.84 ± 0.04 m. Sinker root size and rooting depth decreased with distance along the horizontal roots (Table 3.2). No significant relationship existed between the mean total number of sinker roots and any stem size variable. The ratio between lateral and sinker roots with regard to total root number was 0.58 and 0.42 respectively. The maximum depth of all taproots, which occurred at base of the stem-root joint, was 85.36 ± 4.03 m.

Table 3.2. Root architecture and morphology of all major structural roots of 33-year old *P. pinaster* trees in the study area relative to distance from tree trunk: a). lateral roots, b). sinker roots, and c). tap roots (data are means ± standard error). Where letters in superscript differ, $P < 0.05$.

| | Distance from stem (m) | | | |
|---|---|---|---|---|
| a). Lateral roots | 0.2 | 0.5 | 1.0 | 1.5 |
| No of roots | 12.3 ± 0.7[a] | 11.8 ± 0.7[a] | 9.2 ± 0.6[b] | 2.7 ± 0.3[c] |
| Mean *CSA* (mm²) | 295 ± 31.0[a] | 144 ± 16.0[b] | 67.0 ± 7.0[c] | 29.0 ± 4.0[c] |
| Mean total *CSA* (mm²) | 3565 ± 351[a] | 1653 ± 194[b] | 637 ± 88[c] | 86 ± 16[c] |
| Mean eccentricity (*e*) | 0.40 ± 0.02[a] | 0.43 ± 0.01[a] | 0.41 ± 0.02[a] | ND |
| | Distance class from stem (m) | | | |
| b). Sinker roots | 0.0 – 0.19 | 0.20 – 0.49 | 0.50 – 0.99 | 1.0 – 1.5 |
| Maximum depth (m) | 0.75 ± 0.05[a] | 0.80 ± 0.04[a] | 0.56 ± 0.05[b] | ND |
| Mean no of roots | 3.25 ± 0.59[a] | 4.53 ± 0.43[b] | 1.81 ± 0.34[c] | ND |
| Mean *CSA* (mm²) | 276 ± 71 [a] | 163 ± 17 [a] | 82 ± 9 [b] | ND |
| Mean total CSA (mm²) | 710 ± 117[a] | 704 ± 120[a] | 169 ± 37[b] | ND |
| c). Tap roots | | | | |
| Mean *CSA* (mm²) | 3733 ± 374 | - | - | - |
| Maximum depth (m) | 85.36 ± 4.03 | - | - | - |

ND = not enough data available

The mean CSA of first order lateral roots decreased significantly from 295.0 ± 31.0 mm² at a distance of 0.2 m from the trunk to 29.0 ± 4.0 mm² at 1.5 m from the stem ($F_{3, 74} = 41.0$, $P < 0.001$, Table 3.2). The mean total CSA of all first order lateral roots also decreased significantly with distance (Table 3.2, $F_{3, 74} = 52.46$, $P < 0.001$), with the highest value of (3565 ± 351 mm$^2$) at a distance of 0.2 m from the stem base.

Total root CSA at 0.2 m from the stem for all trees increased significantly with DBH, but $R^2$ was low ($y$ = 29.8$x$ - 408, $R^2$ = 0.33, P < 0.01). When stem CSA was regressed against total root CSA, a significant positive relationship was found but again $R^2$ was low ($y$ = 0.425$x$ + 371, $R^2$ = 0.32, P = 0.05). No significant relationships were found between total root CSA and any other root or shoot variable.

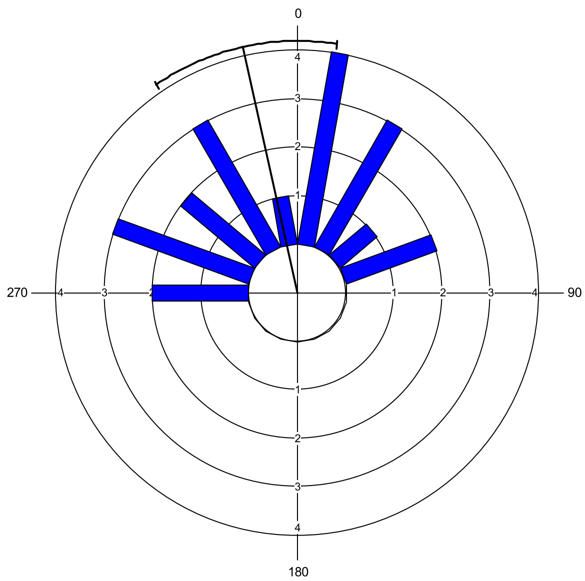
Lateral root distribution analysis

Mean azimuth when all first order lateral roots were considered together was 352.0° ± 48.8° and these roots were significantly clustered in this direction ($r$ = 0.70, Rao's spacing test: P < 0.01, Figure 3.6a). When root CSA was taken into consideration, the centre of root mass shifted slightly to a mean azimuth of 347.4° ± 50.0° ($r$ = 0.68, Rao's spacing test: P < 0.01) indicating significant clustering of the root system, (Figure 3.6b), with mean root CSA clustered towards the NW.

Root eccentricity

No significant differences were found in $e$ with distance from the tree trunk. Only a slight change in $e$ was recorded, with the highest value of 0.43 ± 0.01 to 0.41 ± 0.02 at a distance of 0.5 and 1.0 m, respectively (Table 3.2). No significant relationships were found between root $e$ and any other tree parameter.

a).




b).

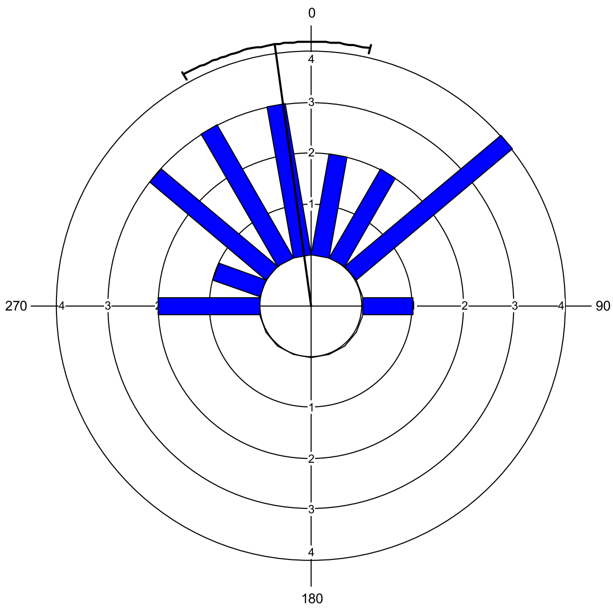



Figure 3.6. Orientation of mean center of root cross-sectional area (CSA) of all trees relative to azimuth direction. a). Significant clustering of first order lateral roots towards an angle of 352.0 ± 48.8° (solid line) occurred when the mean azimuth was calculated with regard to north (where winching direction = 0°). b). When first order lateral root CSA for all trees with regard to winching direction was determined, significant clustering of first order lateral roots occurred towards an angle of 347.4 ± 50.0°. Each bar indicates the mean orientation of first order lateral roots for each tree and the solid line indicates the direction of clustering of center of CSA for all trees.

Relationship between root system anchorage and morphology

When $TM_{crit}$ was regressed against various root and shoot morphological characteristics for control trees, highly significant relationships were found with stem DBH, $DBH^2$, $DBH^3$, no of sinker roots and total CSA of first order lateral root (Table 3.3). Highly significant relationships were also found when $TM_{crit}$ was regressed against combination of parameter such as root CSA, tree dimension and relative root depth, when trenching was made at 1.0 m and 0.5 m respectively. For trees where roots were cut at a distance of 1.5 m from trunk, TARS was best regressed with single predictor such as tree dimension (DBH and tree height), and a combination of predictors e.g. DBH, total and relative root depth and tree height (Table 3.3). In trees where roots had been cut at a distance of 1.0 m from the stem, significant relationship between TARS with single (root CSA) and combination of parameters (e.g. root CSA, taproot length and diameter, relative and total root depth, tree height and number of sinkers), however variability was high. No significant relationships existed between any shoot or root variable and TARS in trees where roots had been cut at a distance of 0.5 m from the stem.

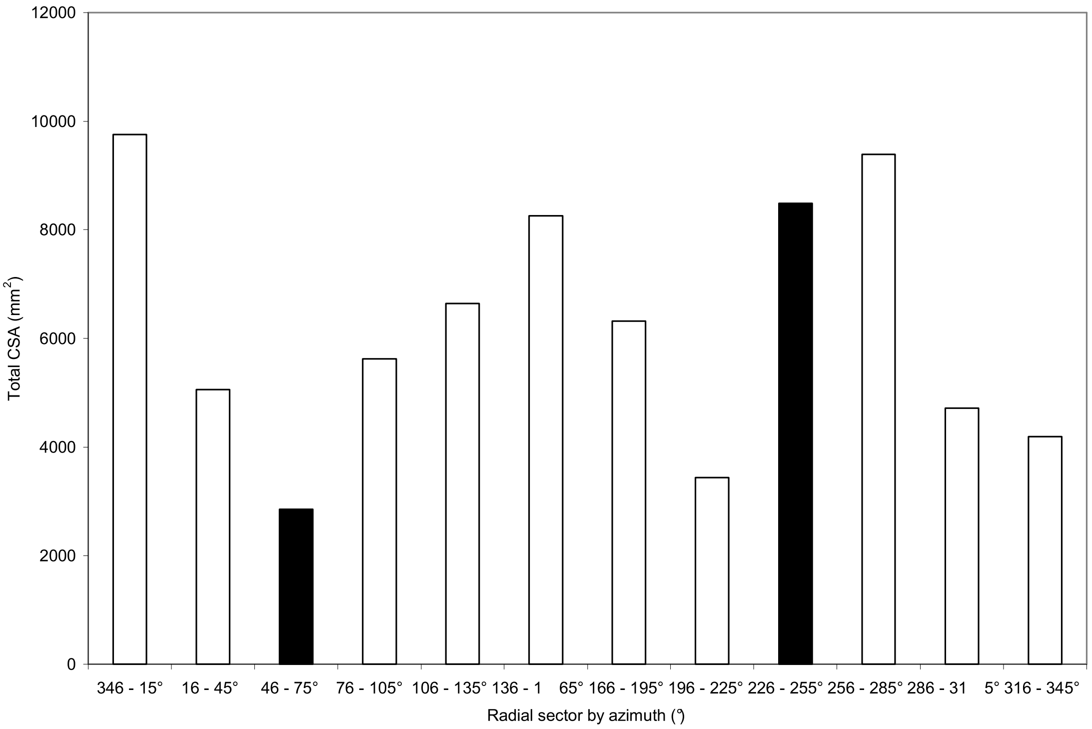
Table 3.3. Linear regressions between $TM_{crit}$ or tree anchorage rotational stiffness (TARS) and various tree physical parameters at different distances from the tree trunk (in order of decreasing $R^2$).

| Regression equation | $R^2$ | P |
|---|---|---|
| Control trees | | |
| $TM_{crit}$ = 59 - 000845 DBH$^3$ | 0.99 | 0.026 |
| $TM_{crit}$ = 65.3 - 0.313 DBH$^2$ | 0.99 | 0.039 |
| $TM_{crit}$ = 84.3 - 1.55 DBH | 0.99 | 0.05 |
| $TM_{crit}$ = 36.6 + 1.24 No of Sinker Roots | 0.93 | 0.05 |
| $TM_{crit}$ = 22.9 + 0.170 Total CSA 0.5m | 0.92 | 0.009 |
| Trees with roots cut at 1.5 m distance from the stem | | |
| TARS = - 0.44 + 0.133 DBH | 0.23 | 0.045 |
| TARS = - 2.31 + 0.274 Tree Height | 0.23 | 0.046 |
| TARS = 1.27 + 0.00256 DBH$^2$ | 0.21 | 0.05 |
| TARS = - 2.20 + 0.123 DBH + 39.6 Relative Root Depth | 0.43 | 0.019 |
| TARS = - 1.82 + 0.116 DBH + 0.0155 Total Root Depth | 0.37 | 0.041 |
| TARS = - 2.53 + 0.195 Tree Height + 33.5 Relative Root Depth | 0.34 | 0.05 |
| Trees with roots cut at 1.0 m distance from the stem | | |
| $TM_{crit}$ = -20.4 + 0.0335 Total CSA 0.2m on Compression Side + 1.67 DBH | 0.89 | 0.011 |
| $TM_{crit}$ = -25.6 - 0.039 Mean CSA 0.2m + 3.69 Tree Height | 0.87 | 0.046 |
| $TM_{crit}$ = 25.9 + 0.195 Total CSA 1.0m | 0.62 | 0.036 |
| TARS = 3.47 - 0.0658 Mean CSA 0.5m | 0.41 | 0.01 |
| TARS = - 0.0330 Mean CSA 0.2m + 3.49 | 0.34 | 0.022 |
| TARS = - 0.00244 Total CSA 0.2m + 3.43 | 0.23 | 0.049 |
| TARS = 4.53 - 0.0122 Taproot length - 0.0662 Mean CSA 0.5m | 0.49 | 0.018 |
| TARS = 4.77 - 23.0 Relative Root Depth - 0.0736 Mean CSA 0.5m | 0.49 | 0.018 |

| | | |
|---|---|---|
| TARS = 1.35 + 0.114 Tree Height - 0.0716 Mean CSA 0.5m | 0.45 | 0.027 |
| TARS = 4.34 - 0.00697 Total Root Depth - 0.0695 Mean CSA 0.5m | 0.45 | 0.029 |
| TARS = 4.53 - 0.0331 Mean CSA 0.2m - 0.0120 Taproot Length | 0.42 | 0.039 |
| TARS = 3.40 + 0.0164 Mean CSA 0.2m - 0.0944 Mean CSA 0.5m | 0.42 | 0.039 |
| TARS = 0.85 + 0.145 Tree Height - 0.0385 Mean CSA 0.2m | 0.41 | 0.042 |
| TARS = 3.43 + 0.00035 Total CSA 0.2m - 0.0722 Mean CSA 0.5m | 0.41 | 0.042 |
| TARS = 3.18 + 0.0113 Taproot Diameter - 0.0634 Mean CSA 0.5m | 0.41 | 0.041 |
| TARS = 3.47 - 0.0633 Mean CSA 0.5m - 0.00021 Total CSA 0.5m | 0.41 | 0.042 |
| TARS = 3.37 - 0.0653 Mean CSA 0.5m + 0.0089 No of Sinker Roots | 0.41 | 0.041 |
| TARS = 4.86 - 0.00269 Total CSA 0.2m - 0.0155 Taproot Length | 0.39 | 0.05 |
| TARS = 2.37 + 0.0383 Taproot Diameter - 0.00434 Total CSA 0.5m | 0.39 | 0.05 |
| Trees with roots cut at 0.5 m distance from the stem | | |
| $TM_{crit}$ = -52.0 + 0.0981 Mean CSA 0.5 + 1298 Relative Root Depth | 0.74 | 0.035 |

The relationship between Σ root CSA in each of the twelve 30° radial sectors and TARS was significant in only two sectors, along the direction of bending: 46 – 75° and 316 – 345° (Figure 3.7). Σ root CSA was significantly correlated with TARS in two sectors on the WW side of the tree (R = 0.78, P = 0.003; R = 0.8, P = 0.01, Figure 3.7a). However, no significant correlations were found between TARS and root number. A significant negative correlation was also found between TARS and the ratio of CSA of first order lateral roots with root number in the WW sector 346 - 15° (R = -0.78, P = 0.001; Figure 3.7b) and sector 316 - 45° (R = -0.87, P = 0.002) and the opposite side of WW sector 196 - 225° (R = 0.72, P = 0.027, Figure 3.7b).

a).




b).

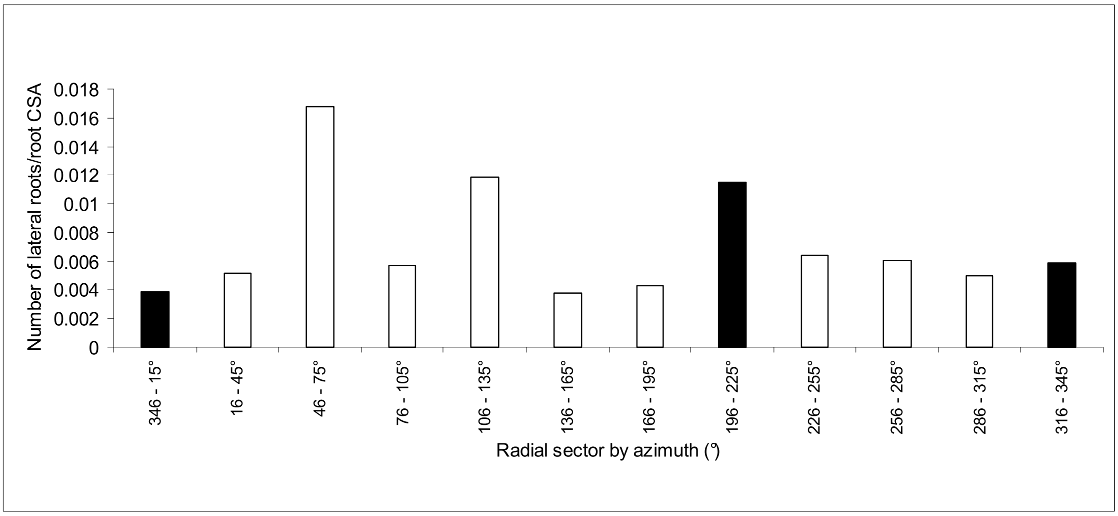



Figure 3.7. Relationship between a) total root CSA and b) ratio between number of first order lateral root and total root CSA with regard to bending stiffness before cutting in each of the twelve 30° radial sectors. The counter-winchward direction was considered to be at 0°. (Black bars indicate sectors where Pearson's correlations were significant at $P < 0.05$).

## Discussion

The trenching method used for this study was easy to apply and provided us with useful results, although it was not possible to determine the influence of individual roots on anchorage mechanics. By analysing the relationships between $TM_{crit}$ or TARS and tree morphological characteristics, we were able to determine several mechanisms involved in root anchorage. The result of this study showed that a significant difference existed between RARS with different trenching distances from the tree trunk. The effect of trenching on TARS ranged between 9 to 30%, and was significantly different when roots were cut at a distance of 0.5 and 1.0 m from the tree trunk. Surprisingly, no significant differences in $TM_{crit}$ were observed, possibly due to the variability observed in the data as root system architecture was highly asymmetric. Trenching therefore appeared to have a direct influence on tree mechanical stability.

The regression analysis between root anchorage and various shoot and root parameter showed that several significant regressions existed between $TM_{crit}$ and different variables in the control group of trees, but the most significant relationships were with single parameters such as DBH, number of sinker roots and total root CSA. No significant relationships were found between $TM_{crit}$ with a combination of parameters, probably because in this group, only few data were available. Significant relationships also existed between $TM_{crit}$ and combinations of parameters e.g. total and mean CSA of first order lateral roots, DBH, tree height, and relative root depth for trees where trenching was performed at a distance of 0.5 and 1.0 m from the trunk. No significant relationship was found in $TM_{crit}$ when trees were trenched at 1.5m from trunk, probably due to a limited number of roots first order lateral roots being observed present at and beyond this distance during the study. However, with regard to tree anchorage stiffness, significant relationships existed between TARS and various shoot and root variables, including single and combinations of parameters such as DBH, tree height, total and relative root depth, taproot size and length, number of sinkers and total root CSA close to the trunk. Thus, the result from this study indicates that when trenching was performed at a distance of 1.0 m from the trunk, first order lateral roots CSA (single parameter) and a combination of above and below ground parameters like taproot length, relative root depth, tree height, number of sinkers, root depth, taproot size as well as CSA of first order lateral were the best predictors of TARS. The significant relationship between tree anchorage and various measures of its size has been proposed earlier by Fraser (1962) and Fraser and Gardiner (1967), who found linear relationships between $TM_{crit}$ and stem weight in Sitka spruce (*Picea sitchensis* Bong. Carr.). Tree height and DBH are often used as standard variables to indicate tree size. As trees grow, self and wind-induced stresses tend to concentrate at the base of the tree where they are transferred, through the roots to the surrounding soil in order to prevent mechanical failure of the tree. The bigger the size of a tree, the larger the stresses that tree must withstand. Woody plants must, therefore, have at least one rigid element in the root system in order to resist the rotational moments transmitted by the stem (Ennos 1993). Despite the fact that deep vertical roots are crucial in sandy soil (Dupuy et al. 2005b), in older trees where rooting depth is often arrested by seasonal water logging or hardpans in the soil as commonly found in the study area where *P. pinaster* trees were grown, taproots are short and thick compared to the lateral roots and play only a small role in tree anchorage (Danjon et al. 2005). Such types of root system are poorly anchored in the soil, especially in wet winters when soil cohesive properties are reduced. Trees with greater rooting depth provide have larger root-soil plates with greater weight and surface area which later increase soil shear strength and root-plate rigidity in sandy soil (Mickovski 2002). The importance of root-soil weight was quantified by Coutts (1986) as between 13 – 45% of the total anchorage system in large trees. In order to compensate for the lack of taproot in these trees, anchorage rigidity is being reinforced either by the presence of a large number of sinker roots beneath or near the stem (Danjon et al. 2005) or by the horizontal lateral roots that may increased in size (Stokes 1999).

Generally, mature root systems of *P. pinaster* are characterized as taproot systems with a large central vertical root and smaller lateral roots (Köstler et al. 1968, Stokes 2002), and a large volume of sinkers (Danjon 2005). Most of these sinker roots (84%) were found to be located at a distance of 0.5 m or beneath the main stem area. Therefore these roots would not be damaged if trenching was carried out at a distance of more than 0.5 m from stem, and could therefore continue to function as a major component of anchorage (Mickovski and Ennos 2003), even though the amount of biomass allocated to these roots was significantly less than that in the lateral roots (Table 3.2). In trees in this study, the clustering of tap and sinker roots underneath the tree stem could be considered as acting like a single, large taproot that anchors the tree like a stake in the ground (Ennos 1993). Similar results were also found by Drexhage and Gruber (1998) in Norway spruce (*Picea abies*) where 90% of sinker roots occurred near the stem-root base. Even though the function of the taproot in stability is said to be reduced in mature trees (Ennos 1993, Mickovski and Ennos, 2004, Stokes 2004), vertical anchorage in *P. pinaster* trees is reinforced by secondary sinkers whose volume averages three times the taproot volume in mature trees (Danjon et al. 2005), together with the taproot, they provide rigidity of the entire root soil plate. This finding is supported by Crook and Ennos (1996) who found that the taproot and windward sinkers constitute up to 75% of the anchorage strength in deep-rooted larch trees. Trees that develop rigid root-soil plates ensure smaller displacements sooner during uprooting and may prevent initial failure in the soil (Coutts 1986). In *P. pinaster*, the ZRT could be considered as being in the region of 0.5 m from the tree stem, with a maximum sinker depth of 1.04 m, located at a distance of less that 0.2 m from the trunk. However, these *P. pinaster* trees were growing where rooting depth is often limited by a high water table and the presence of hard pans in the soil, thus resulting in a significant loss of anchorage stiffness when trenching was performed at a distance of 1.0 and 0.5 m from the tree trunk as compared to 1.5 m. Furthermore, in this unfavourable environment, root systems may develop laterally rather than vertically (Stokes 1999), thus cutting of major lateral roots may significantly reduce CSA of first order lateral roots and root-soil plate size which play an important role in providing anchorage in large trees growing in sandy soil.

Root CSA has been considered as playing a major role in tree anchorage, particularly in roots close to the stem (Nicoll and Ray 1996, Coutts et al. 2000, Nicoll 2000, Chiatante et al. 2003, Danjon et al. 2005), area under greatest load. Tree stability is also enhanced if resources for structural growth are utilized in an optimum manner (Stokes and Mattheck 1996). In wind-exposed trees, resources are redistributed so that the root bases often develop eccentrically (Nicoll and Ray 1996, Stokes et al. 1998, Mickovski and Ennos 2003) with extra growth forming on the upper and lower sides of the root as compared to circular root shape. As the bending rigidity of a root is directly proportional to the fourth power of its diameter (Ennos and Pellerin 2000), such changes in root surface area, even a small increase in diameter can increase bending resistance and root rigidity.  Root *e* results showed that in our study, most radial growth occurred along the horizontal axis of lateral roots, but was not pronounced. Radial eccentricity has been linked to the distribution of strain throughout the root system during mechanical loading (Ennos 1993, Nicoll and Ray 1996, Stokes et al. 1998, Fourcaud et al. 2008). Roots often have greater thickening on the upper sides where strain is high, producing a shape comparable to a "T-beam" close to the trunk on the LW side of the tree where roots were in compression, or "I-beam" shapes further away from the trunk, particularly on the windward side where roots experience tension and bending (Nicoll and Ray 1996, Mickovski and Ennos 2003, Di Iorio et al. 2007). Such changes in root *CSA* can resist bending resistance within the soil more than any other shape with a similar *CSA* (Nicoll 2000) and further increase rigidity of the root soil plate (Nicoll and Ray 1996). Therefore high strains at the stem-root base can cause buttress type root formation with prominent radial growth above the root centre (Ennos 1993, Nicoll and Ray 1996), but if large vertical tap or sinker roots are present such as in *P. pinaster* trees, this eccentric radial growth can be found on the underside of the root (Stokes et al. 1998). In our study, no significant changes in *e* occurred along the roots, and *e* was almost circular. However, we did not measure the position of the biological centre in the roots, as carried out by Stokes et al. (1998), therefore cannot say where radial thickening occurred the most. This result is in agreement with previous study by Mickovski and Ennos (2002, 2003) on both *Pinus sylverstris* and *Pinus peuce* Griseb Which have an eccentricity of 0.52 ± 0.15 and 0.410 ± 0.016, respectively, and vertically eccentric roots are less common in deeply rooted trees where strong anchorage is provided by roots held by a thick matrix of soil (Nicoll and Ray 1996).

The adaptive secondary root growth of lateral roots by external stresses not only alter its morphology, but also contributes towards asymmetrical arrangement of major lateral roots around the trunk (Stokes et al. 1995b, Nicoll and Ray 1996, Coutts et al. 1998, Mickovski and Ennos 2003, Chiatante et al. 2003, Di Iorio et al. 2005, Nicoll et al. 2006). When all the azimuths of all first order lateral roots were analysed, it was found that lateral roots were significantly clustered toward the NW. However, when the centre of mass of all first order lateral roots was calculated, using azimuth angles and weighted by *CSA*, the mean azimuth towards which roots were clustered was shifted slightly towards 347°. This clustering of lateral roots did not affect anchorage, as also found by Mickovski and Ennos (2003) studying *Pinus peuce* Griseb. In our study, results indicated that there was an increased allocation of root biomass on the northern side, particularly towards the NW i.e. the prevailing wind direction. Asymmetric structural root growth in temperate trees is related to genotype (Nicoll et al. 1995), competition between roots for nutrients early on in their development (Coutts 1987), poor planting conditions (Lindström and Rune 1999, Coutts et al. 2000) and mechanical loading e.g. unilateral wind loading (Stokes et al. 1995, Mickovski and Ennos 2003,) or slope orientation (Watson et al. 1995, Chiatante et al. 2003, Di Iorio et al. 2005, Nicoll et al. 2006). The results suggest therefore that the asymmetric root systems observed in these *P. pinaster* trees may in part be due to the mechanical loading from the NW prevailing wind direction as the site was quite exposed to this wind.

Significant positive correlations were also found between TARS before trenching and the number of first order lateral roots along in the direction of bending on the winchward (WW) side at 46 – 75° and 316 – 345º. No correlations were found between TARS and root number in any sector, but as the ratio between *CSA* and root number was significant in three directions (346 – 15°, 316 – 345º and 196 – 225º). This result suggests that an increase in *CSA* on both the WW side (side held in compression) and CW side (side held in tension) of the tree increases anchorage, possibly at the expense of lateral root number. These results are comparable to those found by Coutts (1983), who showed that the thickness of lateral roots on the WW side of the tree will influence positively anchorage rigidity whereas on the CW side, an increase in root number will augment overturning resistance (Stokes et al. 1995).

This study showed that in terms of TARS and $TM_{crit}$, tree mechanical stability was significantly affected by trenching at a distance closer to the trunk in *P. pinaster* trees. As the DBH, number of sinker roots and CSA of first order lateral roots were good predictors of anchorage and are located within a distance of 1 m from the base of the stem, the severing of lateral roots appeared to have a significant effect on anchorage and stability of the mature *P. pinaster* trees. As most of the roots of *P. pinaster* were found in a distance of less than 0.5 m from the stem, this region can also be referred to as the ZRT (Eis 1974), and in *P. pinaster* trees, Danjon et al. (2005) defined this area as a radial distance of 2.2 x DBH which comprised up to 70% of the root volume and can significantly contribute to rigidity of the entire root soil plate. Fourcaud et al. (2008) also suggest that the ratio between taproot length (or central sinkers) and the length of the ZRT is a dominant component of tree anchorage. Despite the fact that deep vertical roots are crucial in sandy soil (Dupuy et al. 2005b), in older trees where vertical rooting depth is often limited by seasonal water logging as commonly found in the study area where *P. pinaster* trees were grown, taproots are often short and thick as compared to lateral roots and play only a small role in tree anchorage (Danjon et al. 2005), whereas in older trees this role is taken over by lateral roots in order to resist bending (Ennos 1993, Crook and Ennos 1996), by having a pronounce I-beam shaped on windward roots at a radial distance of 0.75 and 1.0 m from the stem for both shallow and deep rooted trees (Nicoll and Ray 1996). Therefore, there is strong evidence that by cutting off major lateral root at a distance closer to the tree trunk, at a distance of 1.0 and 0.5 m, will greatly affect root system architecture and number of sinker, which are important anchorage components in mature *P. pinaster* trees growing on a soil with a hard pan and seasonal water logging. This distance does not correspond with the distance proposed by Danjon et al. (2005) which is within the ZRT for the *P. pinaster* trees (2.2 x DBH), but somewhere within a distance proposed by Wessolly and Erb (1998), within approximately 1.0 to 1.3 m from the trunk. The results of this study, if applied to urban or landscape trees, suggest that in mature taprooted trees growing on unfavourable site where vertical root growth are often limited due to the presence of impervious layers in the soil as generally found in the urban areas, number of sinker roots and root CSA are important criteria anchorage to be considered before trenching is carried out near the tree. However, these results cannot be applied to all trees as this will differ depending on species, tree size, soil conditions and tree vigour. More studies still need to be carried out on different species in a variety of conditions, in order to elucidate further the effect of root loss and determine the maximum distance for trenching in landscape trees without jeopardizing the long-term survival and safety of the tree.

# CHAPTER 4: ROOT MORPHOLOGY AND STRAIN DISTRIBUTION DURING TREE FAILURE OF DIFFERENT TREE SPECIES ON MOUNTAIN SLOPES IN THE FRENCH ALPS

Abstract

To determine which are the most important characters governing mechanical resistance to rockfall and wind loading, static winching tests were carried out on three tree species: Silver fir (*Abies alba* Mill.*),* European beech *(Fagus sylvatica* L.*)* and Norway spruce *(Picea abies* L.) in a mixed forest stand. Trees were winched to an angle of 0.25° at the stem base, both up- and downhill in order to compare how the same individual reacts when tested in two different directions. Trees were then winched to failure. Strain gauges were attached to the stem and one up- and downhill lateral root in order to determine the distribution of strain within the tree during overturning. Root morphology was then measured for all trees which uprooted during failure and results correlated with tree strength.

No significant differences were found in the force necessary to winch trees up- and downhill in any species, either to an angle of 0.25° or to failure. Strain was significantly higher in lateral roots of Silver fir than in roots of Norway spruce and European beech when winched downhill. Downhill roots of Norway spruce were largely held in tension when trees were pulled downhill, whereas in Silver fir and European beech, they were held in compression. When trees were pulled uphill, no significant differences were found between species, and strain decreased along the lateral root of downhill roots only.

European beech possessed a significantly greater number of roots than either Norway spruce or Silver fir. Norway spruce possessed a higher proportion of total root length near the soil surface, whereas European beech had the greatest proportion in the intermediate depth class and Silver fir had the highest maximal root depth. Norway spruce had a significantly lower proportion of oblique roots than

the other two species, resulting in a plate-like root system which was less resistant to overturning than Silver fir or European beech.

Key words: rockfall, windthrow, anchorage, winching tests, tree stability, French Alps.

## Introduction

Trees can have a major impact on human activity, not only in towns and parks, but also on a much larger scale. A better understanding of tree mechanics and root anchorage is vital when trees are used in protection forests in mountainous areas such as the European Alps. The use of protection forests against the impact of natural hazards e.g. rockfall and snow avalanches is becoming more and more common in Europe (Brang 2001, Dorren et al. 2004, Dorren and Berger 2006, Hurand and Berger 2002, Motta and Haudemand 2000, Ott 1996). Although it is understood that the structure of the forest plays a vital role in determining its effectiveness as a protective barrier (Jahn 1988, Kräuchi et al. 2000), little information exists concerning the mechanical resistance of different tree species to different types of natural hazards. One particular natural hazard which has been much neglected until recent years, is that of rockfall. Although rockfall results in an isolated impact on a tree, many similarities can be drawn between the tree response to rockfall and other abiotic stresses e.g. wind and snow loading. When trees are subjected to rockfall, they may uproot, break in the stem, or energy may be transferred to the crown, causing it to break (Dorren and Berger 2006). Although research into the fundamental mechanisms resulting in these three types of failure is scanty, a vast number of studies have been carried out on tree failure through wind loading (Coutts 1983, 1986, Crook and Ennos 1996, Cucchi et al. 2004, Gardiner and Quine 2000, Nicoll et al. 2006, Peltola et al. 2000, Stokes 1999), which will provide useful information in the study of tree resistance to rockfall. These data could also be used as input to models of rockfall dynamics (Dorren et al. 2004) and/or fed directly into management and decision support systems (Mickovski 2005) in order to better manage this fragile environment.

Even if a tree species is useful as a barrier against one particular type of hazard, the same species may not be suitable in protecting against a different type of hazard e.g. Norway spruce (*Picea abies* L.) is not especially windfirm (Stokes et al. 2000) nor resistant to rockfall (Hurand and Berger 2002).

However, in preventing snow movement, Norway spruce is highly effective in holding in place the snow mantle (Hurand and Berger 2002). Therefore, it is necessary to determine which species is best suited to a particular function. In the case of rockfall, different types of rockfall exist, including collapsing in mass where the volume displaced is > 5.0 $m^3$. Individual rockfall occurs more often with smaller volumes (< 5.0 $m^3$) displaced (Berger et al., 2002). It is in this latter case that forests can act as a barrier and provide a protective function. When rocks impact against trees, different types of tree failure can occur, including uprooting and stem breakage (Berger et al. 2002). Certain species, particularly angiosperms, appear to be more resistant to failure than others, often sustaining wounds only (Dorren et al. 2005, Dorren and Berger 2006, Stokes 2006). It is not known which species are the most resistant against the impact of rocks, however, foresters have suggested from experience that broadleaf species are more resistant against rockfall impacts, although no particular reasons are given for this hypothesis. Only in the literature concerning wind damage to forests, can comparisons of different species be found with regards to their mechanical resistance (Meunier et al. 2002, Peltola et al. 2000, Stokes et al. 2000). The most common method to compare the likelihood of stem failure or uprooting, is to winch trees sideways until failure occurs (Cucchi et al. 2004, Gardiner et al. 2000, Moore 2000, Stokes 1999, Stokes et al. 2000). Trees may uproot if poorly anchored, or break in the stem if the moment required to resist overturning is greater than that necessary to break the trunk. Certain species e.g. Sitka spruce (*Picea sitchensis* Bong. Carr) are more susceptible to stem breakage and uprooting than others e.g. European beech (*Fagus sylvatica* L.) (Stokes et al. 2000). Very few data exist concerning broadleaf species.

One of the most important factors governing the ability of a tree to withstand breakage or uprooting during a storm, is the morphology of the root system present (Cucchi et al. 2004, Dupuy et al. 2005, Stokes et al. 2000, 2005). Trees with deep and wide spreading root systems will be better anchored than those with superficial roots only (Stokes 2002). The shape and size of a root system is influenced by its immediate environment as well as being inherent to a particular species (Köstler et al. 1968). Trees growing on the thin, rocky soils encountered on mountain slopes may therefore possess different rooting types depending on species. The morphology of the root system may also differ to that of the same species growing in a deep soil on flat ground (Köstler et al. 1968). Therefore, a well-anchored species growing in a particular soil type, may become highly unstable in a different environment (Dupuy et al. 2005, Moore 2000). Although the classification system used by Köstler et al. (1968), whereby root systems are classified into three shapes, shallow "plate" systems and deeper "heart" and "tap" systems, is still used (Dupuy et al. 2005a, Stokes and Mattheck 1996), a more accurate description of root architecture is necessary to determine which parameter(s) govern root anchorage. Dupuy et al. (2005b) determined numerically that root topology and biomass were the most important variables influencing root resistance in tension, and experimental studies on *Populus* sp provide evidence to corroborate this hypothesis (Dupuy et al. 2007).

The distribution of strain in root systems during tree winching studies has also been studied using strain gauges (Ennos 1995, Stokes 1999, Stokes et al. 2000). Strain gauges convert longitudinal deformations of a metal element into an electrical signal, thus indicating how a material is deformed under loading. Using such gauges, Stokes (1999) and Stokes et al. (2000) determined the mechanical behaviour of several forest species. It was found that in trees which broke in the trunk e.g. Maritime pine (*Pinus pinaster* Ait.), and European beech (*Fagus sylvatica* L.), strain was always found to be higher in the stem than in the roots during winching. However, in Douglas fir (*Pseudotsuga menziesii* Mirb.) and Norway spruce (*Picea abies* L.), which broke at the stem base or uprooted, strain was always highest at the root/stem joint and in the root system, respectively. Stokes (1999) also suggested that wood cells responded to local mechanical stress within the root, which was reflected in the strain values, e.g. leeward roots of wind stressed trees possessed significantly higher values of strain.

Therefore, strain measurements in roots and trunks of trees during winching should provide further information about the behaviour of the tree when subjected to mechanical stresses.

In order to better understand the overturning mechanism of trees when subjected to mechanical loading e.g. rockfall or wind stress, three forest species were winched both up- and downhill on an Alpine slope. Although rockfall can only occur as a downhill abiotic stress, wind loading can occur in any direction, and prevailing winds can often be uphill (Achim et al. 2003). Therefore, results from this study will also be useful to foresters concerned with problems of wind instability of plantations on sloping ground (Achim et al. 2003). Strain in stems and roots was measured during winching and root systems were excavated and root morphology measured in order to determine which parameter best governs root anchorage. Results are discussed with reference to a previous study, whereby trees on the same site were winched to failure downslope only (Stokes et al. 2005).

## Materials and methods

### Study site

The study site (Figure 4.1) was situated in the Forêt Domaniale de Vaujany, Vallée de l'Eau d'Olle, Isère (lat 45°12', long 6°3'), France, at an altitude of 1350 – 1600 m. This forest is located on a northwest facing mountain side that can be divided into two areas. First, the rockfall source areas, which are series of steep cliff faces dissected by some denudation niches occurring on top of each other. The mean slope gradient in the source area is 70° up to vertical cliffs. The second part consists of large post-glacially developed talus cones consisting mainly of rock avalanche deposits, snow avalanche deposits and rockfall scree. These large talus cones were formed after deglaciation of the main valley. The retreat of the glacier resulted in tensional rebound of the oversteepened valley slopes. This retreat led to slope instability and landsliding (mainly rock avalanches), which consequently resulted in the build up of the large talus cones (Figure 4.1). During the Holocene (the last 10 000 years), these talus cones have been colonised by vegetation, eventually resulting in a forest cover. Today, the dominant tree species on the site are Silver fir (*Abies alba* Mill.), Norway spruce (*Picea abies* L.), European beech (*Fagus sylvatica* L.), Sycamore (*Acer pseudoplatanus* L.), European ash (*Fraxinus excelsior* L.) and Common hazel (*Corylus avellana* L.). The forested talus cones have a slope gradient of 38 - 42° and act currently as rockfall transit and accumulation zones. Rocks impacting trees can cause damage and are therefore disturbing the forest ecosystem. The other major disturbances are snow creep, snow gliding, snow avalanches, ungulate browsing and wind loading. The effects of the mass movement processes are clearly reflected in the slope relief and in the vegetation as distinct preferential tracks or channels for snow transport and falling rocks. In between the preferential tracks, the forest is dominated by un-even aged Silver fir and Norway spruce and in the preferential tracks the forest is dominated by young European beech, ash and hazel trees. A storm in 1960 resulted in the loss of 2220 $m^3$ of timber throughout the whole forest, of which the surface area is 818 ha (C. Bazin, pers. comm.).

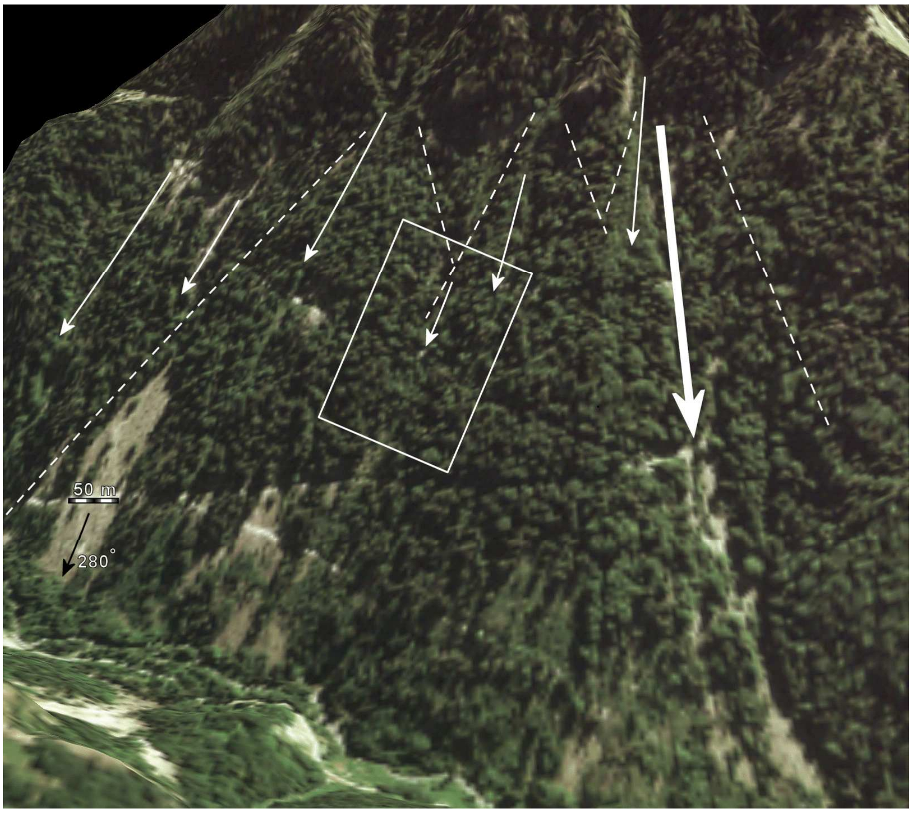



Figure 4.1. A digital terrain model of the study area overlain by an orthophoto. This figure clearly shows that the site consists over several talus cones (dashed white lines) on which preferential rockfall and avalanche tracks exist (white arrows; the size indicates the magnitude of processes acting in the preferential track). The study site is depicted by the white rectangle.

Tree selection

To determine if tree resistance to bending differed when loaded up- and downhill, static winching tests were carried out on 31 trees, selected from 423 trees surveyed in the earlier study (Stokes 2005a). The diameter and spatial position (Figure 4.2) were measured and located. Three species were compared: Silver fir (*Abies alba* Mill., n = 12, mean DBH = 0.23 ± 0.13 m), Norway spruce (*Picea abies* L., n = 10, DBH = 0.24 ± 0.09 m) and European beech (*Fagus sylvatica* L., n = 9, DBH = 0.23 ± 0.18 m) (means are ± standard error). Trees were growing at an altitude of 1350 – 1600 m in the Forêt Domaniale de Vaujany, Vallée de l'Eau d'Olle, Isère, France, facing on a north-west slope with a gradient of 38 – 42°. Rockfall and windstorms are frequent in the area.

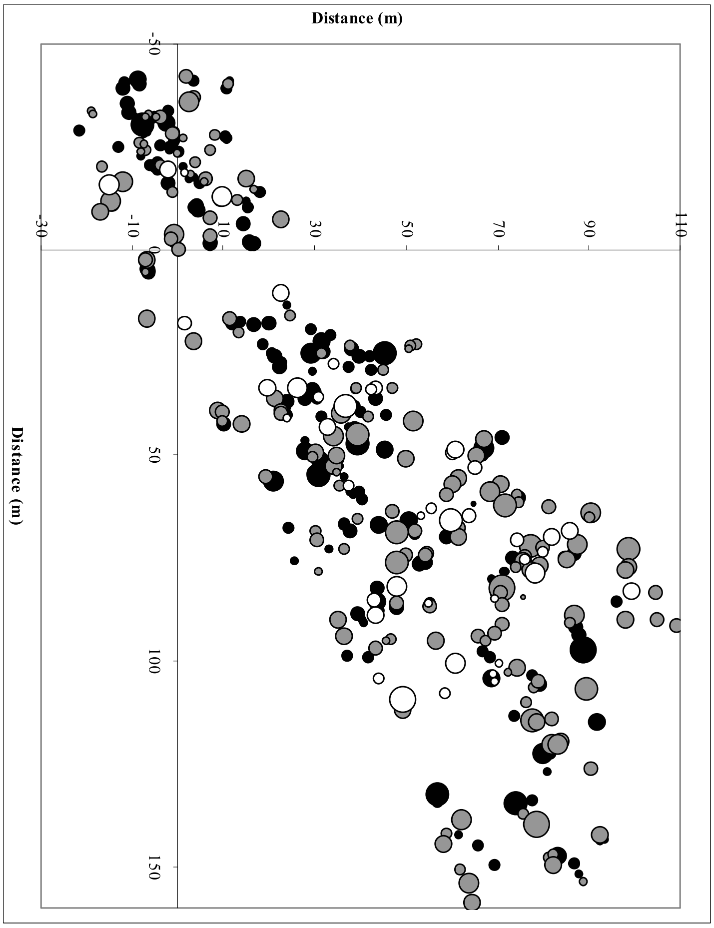



Figure 4.2. A map of the trees measured in an active rockfall corridor in the French Alps. The size of each symbol is representative of tree basal area. Symbols have been enlarged by 15% for better viewing, although some symbols now overlap. A large number of trees are wounded (gray symbols) and solid arrows indicate where healthy trees (black symbols) have been protected from falling rocks by wounded or dead trees (white symbols). The dotted arrow shows the slope direction and hence the direction of rockfall. The axes cross at 0 m, where an initial GPS reading was taken next to a path through the forest.

Strain measurements

Trees were winched sideways (up- or downhill) and the force required to cause failure was measured using a load cell. For a full description of the site, as well as the winching tests carried out, see Stokes et al. (2005). Each tree was winched uphill as well as downhill. In order to avoid damage to the tree during the winching tests e.g. uphill, the tree was winched only to a maximal stem basal deflection of 0.25°, and then released, before being pulled downhill. Half of the trees were pulled in the uphill direction first, and then pulled to failure downhill. The remaining half were pulled downhill first, before being uprooted or broken when pulled uphill.

Two lateral roots per tree were excavated, one up- and one downhill (along the winching direction). In order to measure strain in these roots during mechanical loading, plastic backed strain gauges (Kyowa, Japan, KFG-10-120-C1-11, 10mm gauge length, 120 ohm resistance) were used to estimate longitudinal strains (Stokes 1999). Strain gauges convert longitudinal deformations of a metal element into an electrical signal and must be connected to a strain indicator (Kyowa, Japan, SD-10) in quarter bridge mode, via a switch and balance unit (Vishay Measurements Group, North Carolina, U.S.A., SB-10), in order for the electrical signal to be converted into micro-deformations (µstrain). Bark was removed with a chisel at DBH and every 0.2 m along the length of a root, starting from the stem-root joint. If it was not possible to attach a gauge every 0.2 m, due to the presence of e.g. another root branch or a stone, the gauge was glued at the closest possible distance. In the data analysis therefore, classes of distance of 0 – 0.20 m, 0.21 – 0.40 m and 0.41 – 0.60 m along the lateral root were used. Care was taken not to damage the surface fibres of the wood during removal of the bark. Strain gauges were glued to the wood where the bark had been removed, using Loctite 401 multi-usage glue, which took approximately 15 minutes to dry.

The initial values of each strain gauge were recorded before winching commenced. The trees were then pulled sideways (up- or downhill) using increments of force of 400N. Strain was measured in each of the gauges after each increment of force had been applied. The tree was winched in one direction up to a maximum deflection of 0.25° at the stem base, during which no plastic deformation or failure appeared to occur. The same procedure was then repeated in the other direction and the tree winched until failure occurred. The difference in the force necessary to winch the tree in both directions was then calculated for each tree. Therefore, we were able to compare tree resistance to deflection in both directions.

Measurements of root system morphology

Once the winching tests were completed, root systems were extracted by cutting the trunk at the base and winching the root system out of the soil. Only 19 root systems were analysed, as for trees that had failed in the stem, it was too difficult to extract the root system due to the steepness of the slope and its instability (falling rocks were frequent during extraction of the root systems). Root systems were then transported to the laboratory for architectural analysis. However, a large number of roots were damaged or lost during the winching and extraction process, therefore most root systems were incomplete.

A topological and geometrical description of the root system was carried out using a low-magnetic field 3D digitiser (3SPACE Fastrak, Polhemus, Long ranger option, www.polhemus.com) driven by the software Diplami (Sinoquet and Rivet 1997). This device is composed of an electronic unit, a transmitter and a receiver. For each digitised point, [*x, y, z*] coordinates and diameter (measured manually) were assessed jointly with the topology i.e. how individual roots are connected to each other through branching (Danjon et al. 1999 a,b, Tamasi et al. 2005).

The excavated root system was turned upside down and fixed in place for digitising. Root orientation was not taken into consideration as many roots had been broken during the winching and excavation process. Data were saved in files and exported to the software AMAPmod (Godin et al. 1997). In AMAPmod software, root systems are represented by "Multiscale Tree Graphs" (MTG) (Godin and Caraglio 1998). A MTG is a topological structure in which root data are organised hierarchically in scales. This organisation allows each individual root to be considered as an axis and each axis as a sequence of root segments, a root segment being the part of the root included between two subsequent digitised points. The root length and volume are thus obtained as the sum of each root segment length and volume. A detailed description of the measurement and analysis techniques is given in Danjon et al. (1999 a,b).

Statistical analysis

Analysis of variance and chi-square tests were carried out to determine if the type of damage sustained was influenced by species and size of trees, using size parameters as covariates where necessary. Analyses of variance were carried out to determine if the number, size, angle and proportion of roots differed between species and between depth classes of 0.0 – 0.39 m, 0.40 – 0.79 m and >0.80 m. Where proportions were calculated, data were arcsine square root transformed prior to statistical analysis. As the best parameters to quantify root anchorage are not single parameters e.g. root volume or root number alone, but a combination of two parameters (Dupuy et al. 2005b), therefore, the following combinations of parameters was also analysed for each tree: total root number x total basal cross-sectional area (CSA) of second order lateral roots, maximal root depth x total root volume, maximal root depth x root number and total root volume x total root number. Regressions were carried out between the critical overturning moment ($TM_{crit}$, Stokes et al. 2005) for each tree and certain root architectural parameters, including the combinations of parameters.

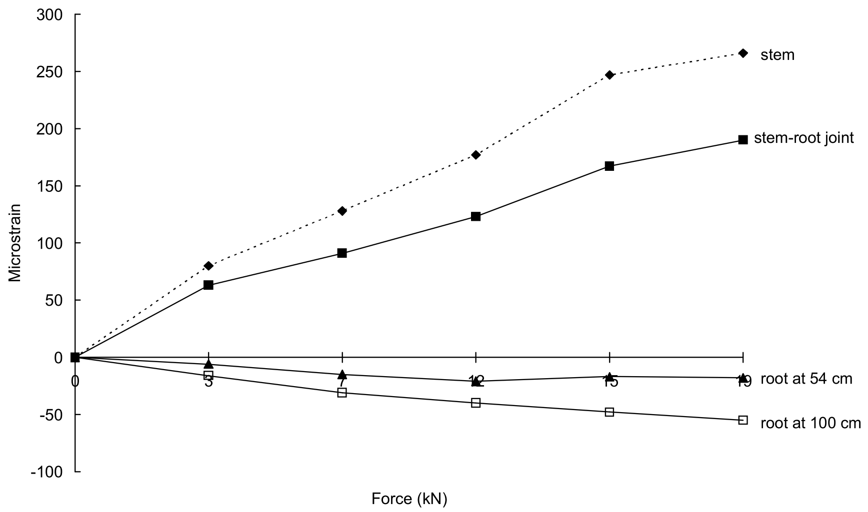
## Results

### Strain measurements

The mean force required to winch a tree uphill to a deflection of 0.25° at the stem base was 6231 ± 2133 N and 3340 ± 1075 N when the tree was winched downhill. No significant differences were found in the force necessary to winch trees in both directions for any species.

Strain was usually found to be highest in the region held in tension where the tree failed (Figures 4.3a,b), but this was only true in 80% of cases. Strain was found to be significantly higher in lateral roots close to the trunk in Silver fir and Norway spruce when winched downhill at a given force of 1500 N (Figure 4.4). Strain at the root base was similar to that in the trunk for Silver fir only (Figure 4.4). When trees were winched downhill, strain at the stem base of Silver fir was significantly greater than in either Norway spruce or European beech (Figure 4.4). In Norway spruce, mean strain at a distance of 0.21 – 0.60 m in the downhill root was found to be in tension whereas the base of the same root was held in compression (Figure 4.5). When trees were winched uphill, no significant differences between species were found and strain was greatest at the stem base in the downhill root only ($F_{5,108}$ = 2.57, P = 0.031).

a).




b).

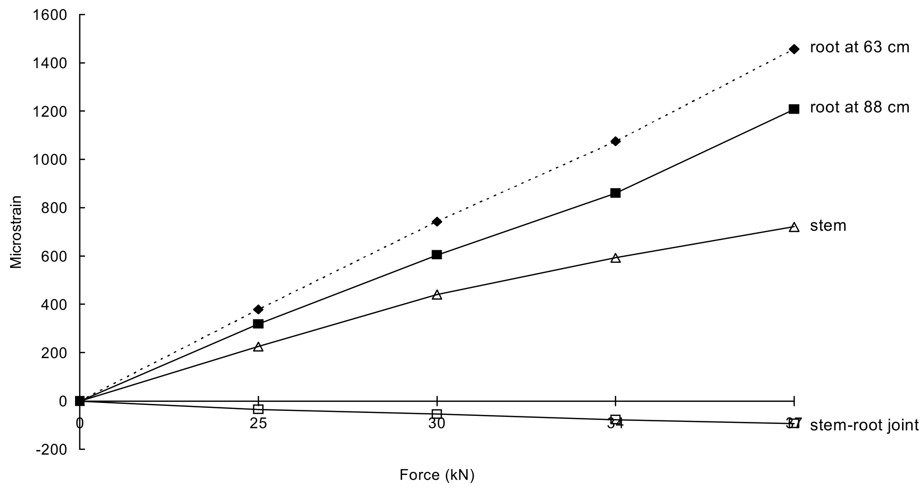



Figure 4.3a). Strain on the counter-winchward (tension) side of Silver fir was significantly greater in the trunk (where failure occurred) as the tree was winched downhill. In b), failure occurred in the root system of European beech when winched downhill, where highest strain values were observed.

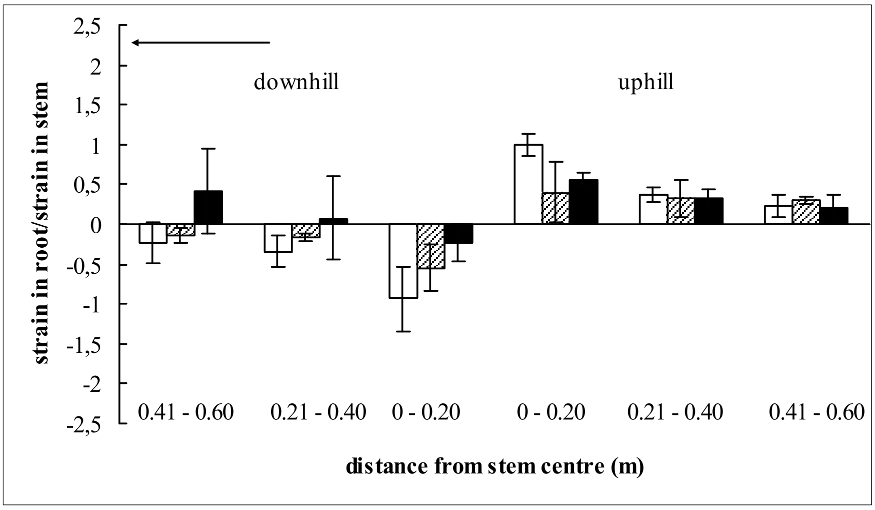
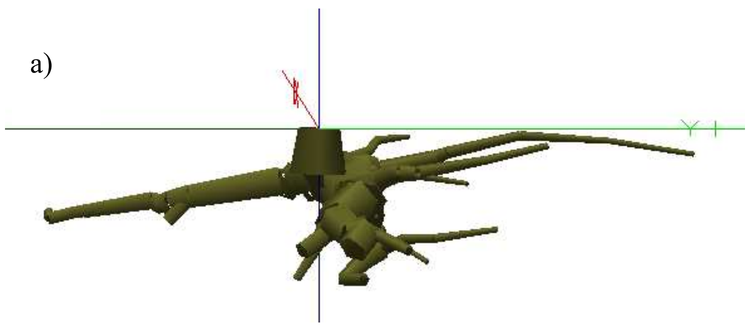



Figure 4.4. Strain along up- and downhill lateral roots of Silver fir (white bar), European beech (shaded bar) and Norway spruce (black bar) when trees were winched downhill (direction of arrow) at a force of 1500 N. Where roots were held in compression, data were changed to negative values for visual purposes only. Strain was significantly greater in Silver fir close to the trunk, than in other species ($F_{2,109} = 3.19$, $P = 0.045$). In Silver fir and Norway spruce, strain differed significantly along the uphill root and in all species, strain decreased in the downhill root ($F_{5,109} = 2.72$, $P = 0.023$). Data are means ± standard error.

Root system morphology

No significant differences were found between species (Figure 4.5) with regards to mean or total volume, or mean or total CSA of second order laterals, even when divided by the equivalent stem parameter.

a)



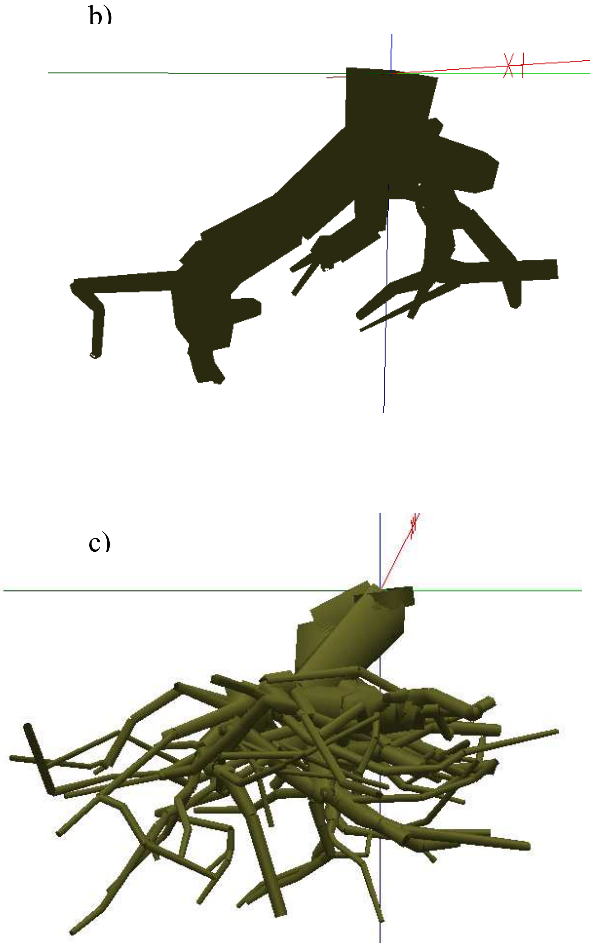



Figure 4.5. Representative root system images of different subalpine forest species. The morphology and topology of each root system was measured and three-dimensional images reconstructed using the method described in Danjon et al. (1999). a) Norway spruce, b) Silver fir and c) European beech. Images provided by F. Danjon, INRA, Bordeaux, France.

European beech had a significantly higher number of roots than Silver fir and Norway spruce (Figure 4.6). The proportion of total root length in each depth class was significantly greater at the most superficial depth for Norway spruce only (Figure 4.7). European beech had the greatest proportion in the intermediate depth class and fir had similar proportions in all three classes (Figure 4.7). Mean maximal root depth in Silver fir was twice that found in Norway spruce or European beech (Figure 4.8). Norway spruce had a significantly lower proportion of oblique roots (0.25 ± 0.09) compared to European beech (0.55 ± 0.03) and Silver fir (0.52 ± 0.09) ($F_{2,14} = 3.73$, $P = 0.05$). No other significant differences were found with regards to root angle between species.

No significant regressions between $TM_{crit}$ and a root architectural variable, including the combinations of parameters, were found for any species when trees were winched to failure either uphill or downhill.

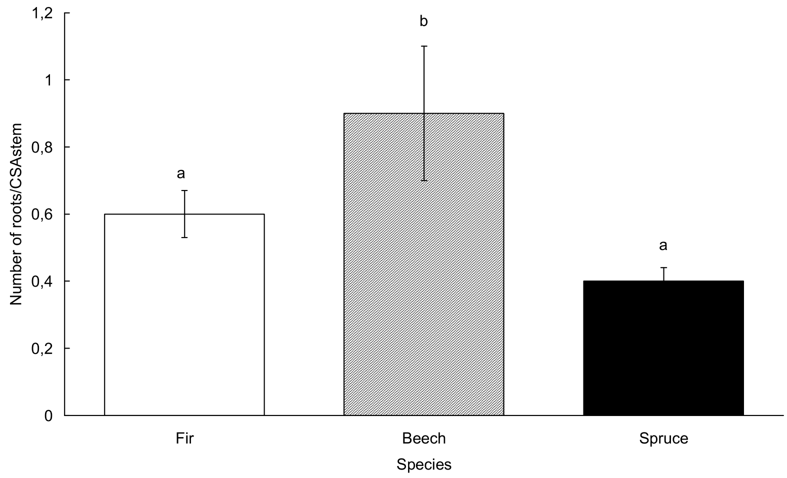



Figure 4.6. European beech (shaded bar) had significantly more roots/CSAstem than Silver fir (white bar) or Norway spruce (black bar) ($F_{2,16}$ = 9.38, P = 0.002). Data are means ± standard error. Where superscripts differ, significance <0.05.

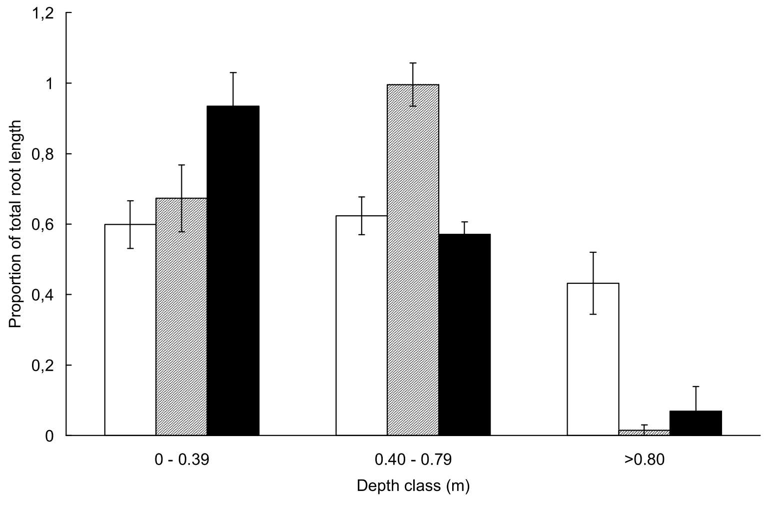



Figure 4.7. The proportion of total root length in each depth class was significantly greater at the most superficial depth for Norway spruce (black bar) only. European beech (shaded bar) had the greatest proportion in the intermediate depth class and Silver fir (white bar) had similar proportions in all three classes ($F_{2,42}$ = 23,94, P<0.001). Data were arcsine square root transformed prior to analysis and are means ± standard error.

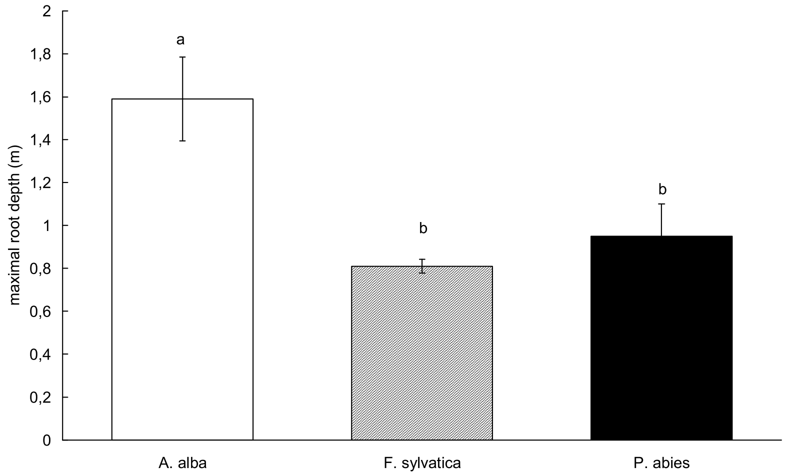



Figure 4.8. Mean maximal root depth was significantly greater in Silver fir (white bar) than in either European beech (shaded bar) or Norway spruce (black bar) ($F_{2,16} = 5.75$, $P = 0.013$). Data are means ± standard error. Where superscripts differ, significance <0.05.

Discussion

In a previous study on the same trees, Stokes et al. (2005) found that European beech was the most resistant species to uprooting, followed by Silver fir, then Norway spruce. Silver fir tended to break in the stem, whereas Norway spruce and European beech generally uprooted. In the present study, it was surprising that no differences were found in root anchorage when trees were pulled uphill, compared to when they were pulled downhill. According to Achim et al. (2003), Sitka spruce (*Picea sitchensis* Bong. Carr.) required a significantly greater moment to uproot when winched uphill. The authors attributed this higher resistance to a possible increase in root development on the downslope side of the tree, although root architecture had not been measured. Meanwhile, Nicoll et al. (2006) measured root architecture in adult Sitka spruce found that prevailing wind direction was as important as the slope effect. However, Di Iorio et al. (2008) who measured root system architecture in *Spartium junceum*, growing on inclined ground showed that soil type influenced significantly root directional growth. Therefore, many variables tend to influence root growth on slopes. Variability was high in our results, which was in part due to the heterogeneous and rocky nature of the soil. Although the number of trees tested was low, each tree was tested in both directions, therefore, any differences in anchorage when trees were pulled in different directions, should have been observed. We assume therefore that any root growth asymmetry along the slope direction was not enough to affect the anchorage moment of the trees tested. It was not always possible to predict where a tree would fail from the strain values, as suggested by Stokes et al. (2000), which may also be due to the heterogeneous nature of the rocky soil. However, strain was higher in the region where failure occurred in 80% of the trees tested, whether winched up- or downhill. Therefore, this method of predicting tree failure can still be considered useful, when combined with other techniques (Mattheck and Breloer 1995).

Unfortunately, many roots were broken and lost during the excavation process, therefore, root systems were not intact and a large amount of variability was thus seen in the results. Trees which had broken in the stem (Stokes et al. 2005) were not excavated due to the difficult and dangerous nature of the work, therefore reducing sample size. European beech, the most resistant species to uprooting (Stokes et al. 2005), possessed twice as many roots as Silver fir or Norway spruce. The proportion of roots with regards to length was also greatest at an intermediate depth in European beech, whereas Norway spruce had the highest proportion of superficial roots and lowest proportion of oblique roots. No relationships were found between any root architectural parameter and $TM_{crit}$ when all species were considered separately, which may have been due to insufficient data, or the fact that root anchorage is much more complex than the analysis used in this study.

Strain was highest at the stem base in Silver fir and European beech when pulled downhill. In Norway spruce, strain was highest at the stem base in the uphill root only, whereas in the downhill root, strain was highest at a distance of 0.41 – 0.60 m from the stem. Strain was also positive between 0.21 – 0.60 m, therefore indicating that downslope roots were largely held in tension when Norway spruce was winched downhill. Norway spruce possessed a highly superficial, “plate-like” root system, with very few oblique roots, therefore, the root plate is lifted out of the soil during overturning (Mattheck and Breloer 1995, Stokes 2002). It is considered that such plate-like root systems are the least resistant to overturning, due largely to their superficial nature (Mattheck and Breloer 1995, Stokes et al. 2000). The position of the root system hinge (point of rotation) plays an important role in the anchorage of plate-root systems (Fourcaud et al. 2008): the closer the hinge is to the trunk, the less efficient is the anchorage resistance (Coutts 1983, 1986). In Norway spruce, it can be assumed that the hinge on the winchward side of the tree was situated very close to the trunk, where strain values were close to zero, which may also explain the low anchorage resistance of this species (Stokes et al. 2005).

Silver fir and European beech possessed deeper rooted systems with a higher proportion of oblique roots. When deeper rooted systems with a large number of branches overturn, e.g. European beech, the root-soil ball slides into the soil and is not lifted out of the soil as in Norway spruce (Mattheck and Breloer 1995, Stokes 2002). In Silver fir, however, a tap-rooted system (Kutschera and Lichtenegger 2002), the long tap root will be pushed into the soil on the counter-winchward side of the tree (Crook and Ennos 1997). When European beech and Silver fir were pulled downhill, the winchward roots were placed in compression as they were pushed into the soil. European beech roots were highly numerous and strain values were generally lower, as external loading forces were dissipated through the roots. As Silver fir had a lower number of roots than European beech, higher strain values may be expected around the stem and root bases, as mechanical stresses will be concentrated in fewer roots (Ennos 1995). Silver fir tended to break in the stem during winching, indicating that the moment required to resist overturning was greater than that necessary to break the trunk. Root systems of Silver fir were very deep, and often it was not possible to excavate the entire system, therefore it can be assumed that root depth plays an important role in the anchorage of this species.

It is unfortunate that the orientation of each root was not taken into consideration and no correlations could be made between up- and downhill roots and $TM_{crit}$. It has been suggested several times in the literature that lateral roots held in tension offer the largest resistance to overturning (Coutts 1983, 1986, Crook and Ennos 1996, Stokes 2002), therefore these roots should have been examined more closely. If tap and sinker roots are present, these roots may also contribute significantly to root anchorage (Mickovski and Ennos 2002). Root topology is also an important factor governing tree anchorage (Dupuy et al. 2005b, Stokes et al. 1995), and should be examined in intact root systems. Nevertheless, results from this study indicate that root architecture differs between forest species, which in turn may influence anchorage strength.

This study show that different forest species do not possess the same mechanical resistance to rockfall or wind loading, and that no single underground parameter could be identified which correlates with

$TM_{crit}$. Anchorage may be determined by a combination of parameters which is species dependent, e.g. biomass, topology and geometry, which would necessitate a more complex analysis than that carried out in this study (Dupuy et al. 2005a,b). An initial study of anchorage should be carried out on many trees of one species growing on flat ground, in order to remove the slope variable. Aboveground parameters, e.g. DBH or stem mass are therefore sufficient for use in models concerned with the prediction of overturning resistance for these species on this type of study site (Stokes et al. 2005). Wood strength of species was not taken into consideration in this study even though it is a factor which will strongly determine stem breakage and should also be examined in future studies of tree resistance to mechanical loading (Dorren and Berger 2006). Putz et al. (1983) suggested that larger trees with dense, strong wood were more prone to uprooting than stem snapping, and this may be particularly true in a forest where the abiotic stress is rockfall rather than wind loading.

# CHAPTER 5: CONCLUSION AND DIRECTION FOR FUTURE RESEARCH

Conclusion

Chapters Two to Four presented the results of the experiments performed on different tree species with intrinsically different root architectural patterns, growing on different types of soil. Through tree winching and trenching tests, $TM_{crit}$. and anchorage stiffness required to break or uproot a tree was calculated and quantified. Together with root architecture analysis, the best predictors associated with anchorage and stiffness of mature tropical and temperate species were determined. Generally, the results from these studies suggest that different types of root systems anchor the tree in different ways and that root adaptation can occur to adjust to the surrounding environment.

The results of the study in Chapter Two showed that in sandy clay soil the removal of major structural roots through trenching only slightly modifies the anchorage of mature tropical urban trees of *E grandis*. Surprisingly, no significant differences were found between $TM_{crit}$ and TARS with trenching distance, even when trenching was carried out close to the stem, at a distance of 0.5 m. One possible explanation to this finding is probably due to high variability found in the root system of *E. grandis*, where root system architecture was highly asymmetric. This explanation is supported by the root clustering analysis which showed a preferential clustering of first order lateral roots towards North-West and North-East directions, i.e. along the prevailing wind directions and which also corresponded to the upslope direction. Such asymmetric growth is considered as an adaptive strategy which improves tree anchorage (Stokes et al. 2007). Therefore, if we had winched our test trees along e.g. the direction of most growth or the prevailing wind direction and not at random, as suggested by Stokes (1999) and Cucchi et al. (2004), more significant results with regard to trenching may have been observed. Our analysis on the root system morphology also revealed the presence of a large number of vertical sinkers close or beneath the stem base, with the maximum depth located close to the stem. As a result, these roots would not be damaged by trenching, and could therefore continue to function as major component of anchorage. As the tree grows, loading stresses tend to concentrate at the base of the tree from where they are transferred, through the roots to the surrounding soil. Therefore, in order to dissipate this localised and potentially damaging concentration of stresses, adaptive growth in the form of biomass is located to those parts of the stem or roots systems under greatest load (Nicoll and Ray 1996). A major consequence of this additional biomass is to decrease root flexibility, which in turn decreases movement and thereby improves tree stability (Blackwell et al. 1990). This adaptation can be clearly seen in this study where root *e* was found to be high close to the trunk, with most growth along the vertical bending axis. Such changes in root *CSA* can resist bending resistance within the soil more than any other shape with a similar *CSA* (Nicoll 2000) and further increase rigidity of the root soil plate (Nicoll and Ray 1996).

Despite the complexity of the mechanisms involving anchorage and the interaction between root-soil parameters as shown in this study, Chapter Two also provides us with important information on several mechanisms involved in the anchorage of the trees under investigation. The regressions results suggest that in sandy clay soil, rooting depth and root plate size are the best predictors for anchorage and therefore are important criteria to consider before trenching is carried out. As root plate radius is correlated to stem radius, this simple relationship can therefore be adapted to many species in different environments (Mattheck and Breloer 1995).

The local environment, particularly the soil type can have a strong influence on the resistance to uprooting and the mechanisms of failure (Dupuy et al. 2005) as well as the shape of the root system. The results of the study presented in Chapter Three showed that in *P. pinaster* trees grown in sandy podzol soil, no significant relationships were found with regard to the effect of trenching on $TM_{crit}$. However, TARS was modified depending on the position of trenching particularly when close to the stem. Despite being acknowledged as deep-rooted species when soil depth is not limiting, the rooting depth in this species is often arrested by the presence of a high water table or a hardpan in the soil, commonly found in the study area where our *P. pinaster* trees were grown. As a result, taproots are short and thick compared to the lateral roots and play only a small role in tree anchorage (Danjon et al. 2005). Such types of root system are thus relatively poorly anchored, especially in sandy soil where root depth is an important factor because shear resistance increases with depth, due to changes in friction angle (Whitlow 1995). Trees with greater rooting depths also have larger root-soil plates with greater weight and surface area which later increase soil shear strength and root-plate rigidity in sandy soil (Mickovski 2002). In order to compensate for the lack of taproot in these trees, anchorage rigidity is being reinforced either by the presence of a large number of sinker roots beneath or near the stem (Danjon et al. 2005) or by the horizontal lateral roots that may increase in size (Stokes 1999), usually found at a distance between 0.5 m from the stem. Therefore, the removal of these roots through trenching which are crucial in providing anchorage and stability in these trees can result in a significant loss in the anchorage and stability of the trees, as shown in this study. As most of the roots of *P. pinaster* were found in a distance of 0.5 m from the stem, also referred to as the ZRT, Danjon et al. (2005) defined this area as a radial distance of 2.2 x DBH in mature *P. pinaster* trees. Therefore, this simple equation can be adapted to *P. pinaster* trees in order to determine the location where most sinkers are located and where root loss through trenching will have the greatest effect on anchorage.

The results in Chapter Four revealed that most Silver fir (*A. alba*) trees failed in the stem, whereas Norway spruce (*P. abies*) usually failed through uprooting. Despite having very few roots, Silver fir roots were thick and long and able to penetrate between the numerous rocks present in the soil. Therefore, it can be considered that they are well anchored, as the moment required to resist overturning was greater than that needed to cause stem failure. Norway spruce on the other hand, possessed more superficial root systems with few roots, whereas root systems of European beech

(*Fagus sylvatica*) were highly branched and deeper than spruce. Therefore, European beech was the most resistant species to failure, and mean $TM_{crit,}$ was nearly double that of Silver fir and was three times larger than in Norway spruce. The best regressions between $TM_{crit}$ and tree size parameters were found to be DBH and total biomass in European beech and crown biomass in Silver fir.

Despite showing that European beech was the most resistant species to uprooting, followed by Silver fir, then Norway spruce, results from Chapter Four also showed no differences in root anchorage when trees were pulled uphill compared to downhill. Strain distribution was also found to be closely associated to the type of root system. In superficial or plate-like root systems like Norway spruce, strain was highest at a certain distance from stem, thus confirming the previous finding (Stokes et al. 2005) that they are least resistance to overturning. Meanwhile in deeper root systems such as those found in Silver fir and European beech, strain was more pronounced at the stem - root base, indicating that the moment required to resist overturning was greater than that necessary to break the trunk.

In conclusion, there is strong evidence from our results that trees growing in different environments i.e. climate, soil properties and topography, possessed different types of biomechanical strategies to adapt to the surrounding environment. In *E. grandis* trees grown on sandy clay soil, despite the absence of the taproot, anchorage was reinforced by the secondary sinkers located close to or beneath the stem, therefore was not significantly affected by root removal during trenching. Tree anchorage was also enhanced when resources were redistributed so that the root bases often develop eccentrically with extra growth forming on the upper and lower sides of the root as compared to a more circular root shape. Such changes in root surface area, thus increase bending resistance and root rigidity and anchorage which is closely related to tree dimensions and root plate diameter. However, in *P. pinaster* trees with a taproot system growing in an environment where vertical root depth is often arrested by mechanical impedance, the presence of a large number of sinkers close to the trunk, within the ZRT play a major role in anchorage and stability of the tree. Anchorage stiffness in these trees was governed by a combination of several factors such as DBH, stem height, number of sinkers, total and relative root depth. The results suggest that anchorage in these trees was determined by the size and number of sinkers and rooting depth. With regard to $TM_{crit}$, results from Chapter Two and Three showed that $TM_{crit}$ was higher in *P. pinaster* as compared to *E. gradis* despite of growing in sandy podzol soil and in an environment where the vertical growth of roots is often limited by the presence of impervious layers in the soil such as a hard pan, thus resulting in the formation of a shallow root system. Although the role of taproot is reported to be less significant in mature trees, together with the sinker and lateral roots within the ZRT, they provide rigidity to the entire root-soil plate. This finding is further supported by the regression analysis which showed that *P. pinaster* was more resistance to failure than *E. grandis* when $TM_{crit}$ was regressed with $DBH^2$ and $DBH^3$. The results of this finding suggest that the root system architecture is crucial in providing anchorage and stability in mature trees.

For trees growing in a mountainous landscape area, their resistance to rockfall is also closely related to root system architecture. Trees which possess deep roots e.g. Silver fir and beech, were found to be more resistant to uprooting or rockfall as compared to trees with shallow or plate-like root systems, e.g. Norway spruce. In deep-rooted trees, anchorage was mainly governed by the presence of a taproot (Silver fir) or a greater proportion of roots (European beech), whereas spruce only possessed a higher proportion of total root length near the soil surface, resulting in a plate-like root system which was less resistant to overturning than Silver fir and Norway spruce. Therefore, with regard to rockfall protection, the results suggest that beech would be a better species to be used as compared to fir or spruce. Although fir also possess deep rooted root characteristics, beech was found to be able to regenerate better after damage, and produce large numbers of scar tissue if wounded by a rockfall. However, even though if a tree species is useful as a barrier against one particular type of hazard, the same species may not be suitable in protecting against a different type of hazard in the mountainous areas e.g. Norway spruce (*Picea abies* L.) is not especially windfirm (Stokes et al. 2000) nor resistant to rockfall (Hurand and Berger 2002). However, in preventing snow movement, Norway spruce is highly effective in holding in place the snow mantle (Hurand and Berger 2002). Therefore, it is necessary to determine which species is best suited to a particular function.

Directions for future research

The experimental results obtained from these studies have provided a certain amount of detailed information concerning the biomechanics and root system architecture of both tropical and temperate landscape trees grown in different environments. Yet, they are limited to trees growing in a specific situation and therefore the results cannot be applied to all trees as this will differ depending on species, tree size, soil conditions and tree vigour. Therefore, more studies are still needed on different species in a variety of conditions, in order to provide further insight and new knowledge pertaining to the anchorage and morphology of various types of trees in landscape areas as well as to better understand the relationship and interaction between these parameters.

Investigating the anchorage of mature trees is often complicated and time-consuming due to the morphological changes and complexity that occurs in both roots and soil (Danjon et al. 2005), as well as their multi-factorial aspects (Stokes et al. 2005). In order to assist in the interpretation of complex experimental data or in testing and identifying parameters that need to be studied, an alternative to difficult field experiments is through modelling approaches, such as numerical modelling using the Finite Element Method (FEM). Through this type of analysis, certain parameters eg. shoots, roots and the local soil environment, could be analysed and modified to determine the effect of these parameters on tree anchorage, and studied simultaneously (Fourcaud et al. 2008). However, due to difficulties in simulating actual field conditions, some simplifications or hypotheses have often been made which might not represent actual properties and behaviour of variables studied e.g. many trees, particularly urban broadleaf species should not be modelled using cantilever beam theory because they do not have a single tapering stem, thus reducing the reliability of the model. Therefore, in order to avoid such problems, further research should also include testing or validating results found from modelling with actual field experiments (Dupuy et al. 2007). Devising a numerical model based on experimental data obtained from field experiments is crucial for providing real-model similarity.

In recognizing the importance of tree characteristics as well as soil properties where root systems were embedded, several factors should be taken into consideration when investigating root anchorage and tree resistance to natural or man-made hazard. In this thesis, wood strength of different tree species was not taken into consideration even though it is one of the factors that strongly determine stem or root breakage, and therefore should also be included in future research. Putz et al. (1983) suggested that larger trees with dense, strong wood were more prone to uprooting than stem snapping, and this statement may be particularly true in a forest where the abiotic stress is dominantly caused by rockfall rather than wind loading. Meanwhile, bark thickness should also be taken into account as it is known to protect living cambium from wounding (Guyette and Stambaugh 2004), and therefore might be related to the severity of cambial damage caused by rockfall. As the type of failure during mechanical loading not only based on tree characteristics, but also on soil type (Dupuy et al. 2005), therefore, future research should also include various soil properties such as soil hydrology, mechanical impedance and shear strength, as they are also often neglected.

To recapitulate, it is clear that the anchorage of different types of root systems are driven by a complex interaction between several parameters, including mechanical loading that a tree must sustain, environmental factors such as climate, topography and soil properties as well as shoot and root characteristics. As our knowledge on root system biomechanics is mainly based on limited species grown in specific environments, an improved knowledge with regard to stability and anchorage of various types of root systems in different species is urgently needed in order to better manage our valuable landscape trees. Therefore, more studies need to be carried out on other species in different types of soil and situations, which will help to further explain the variability and biomechanical behaviour of different types of root systems, or even within the same species grown in different environmental conditions.

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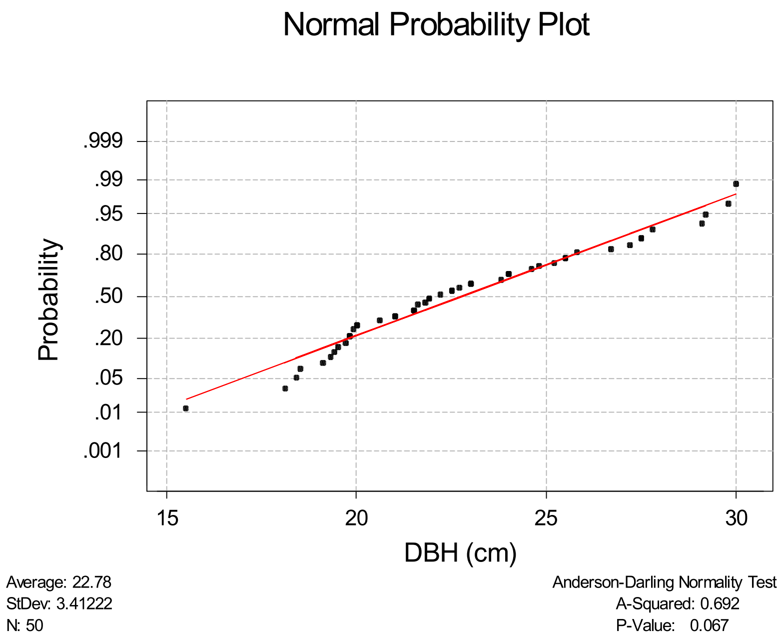
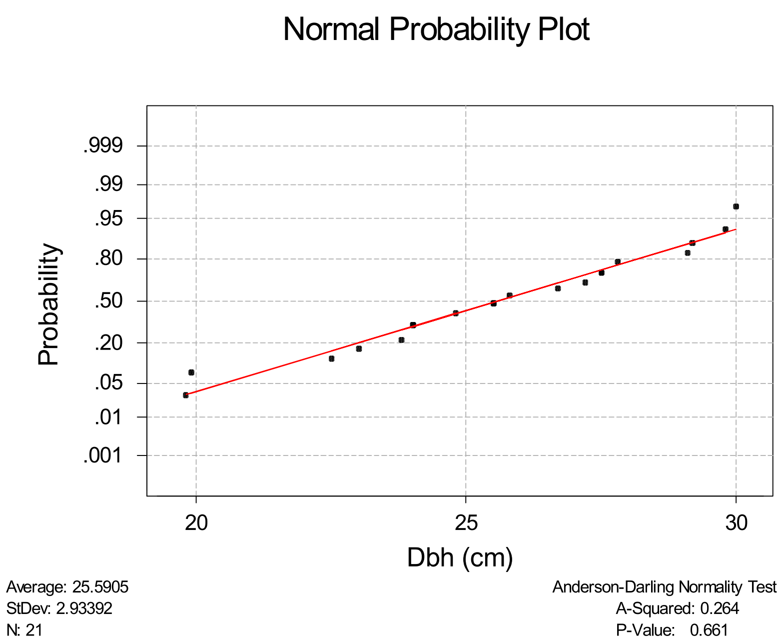
# APPENDICES

**Appendix I** Result of Normality test for *Eugenia grandis* Wight trees.



**Appendix II** Result of Normality test for *Pinus pinaster* Ait trees.



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REVIEW

# The effect of root architecture and root loss through trenching on the anchorage of tropical urban trees (*Eugenia grandis* Wight)

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**Abstract** *Eugenia grandis* (Wight) is grown in urban environments throughout Malaysia and root systems are often damaged through trenching for the laying down of roads and utilities. We investigated the effect of root cutting through trenching on the biomechanics of mature *E. grandis*. The force necessary to winch trees 0.2 m from the vertical was measured. Trenches were then dug at different distances (1.5, 1.0 and 0.5 m) from the trunk on the tension side of groups of trees. Each tree was winched sideways again and the uprooting force recorded. No trenches were made in a control group of trees which were winched until failure occurred. Critical turning moment ($TM_{crit}$) and tree anchorage rotational stiffness (TARS) before and after trenching were calculated. Root systems were extracted for architectural analysis and relationships between architectural parameters and $TM_{crit}$ and TARS were investigated. No differences were found between $TM_{crit}$ and trenching distance. However, in control trees and trees with roots cut at 1.5 m, significant relationships did exist between both $TM_{crit}$ and TARS with stem dimensions, rooting depth and root plate size. TARS was significantly decreased when roots were cut at 0.5 m only. Surprisingly, no relationships existed between $TM_{crit}$ and TARS with any root system parameter when trenching was carried out at 0.5 or 1.0 m. Our study showed that in terms of TARS and $TM_{crit}$, mechanical stability was not greatly affected by trenching, probably because rooting depth close to the trunk was a major component of anchorage.

**Keywords** Biomechanics · Anchorage rotational stiffness · Critical turning moment · Mechanical stability · Acclimation · Root eccentricity

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## Introduction

The presence of trees in urban areas provides many benefits for both the community and environment (Bernatzky 1978; Bradshaw et al. 1995; Miller 1997; Thomas 2000). However, due to their close proximity to infrastructure, mature or large trees can pose significant risks and liabilities especially in an era where the consequences of climate change include a probable increase in windstorms and hurricanes (Quine 1995; Deborah et al. 1996). Therefore, urban trees require special attention, in particular with regard to mechanical stability. Trees in towns and cities are often subject to severe environmental stresses and mechanical damage, especially to root systems, through soil compaction under roads or paving, poor planting conditions, pollution and construction work. With regard to the latter constraint, roots can be heavily damaged through the laying of foundations and trenching during, e.g. construction works and installation of underground utility lines. As most of a tree's roots are found near the soil surface, cutting of roots through trenching can cause serious damage to the root system, resulting in the possible decline or death of the tree. Depending on the distance of the trench from the stem, mechanical stability of the tree may also be compromised (Miller and Neely 1993; Brudi and Wassenaer 2002). Whilst a healthy, vigorous tree can withstand removal of up to 50% of its roots (Heliwell 1985, Sinclair et al. 1987), tree stability may nevertheless be reduced if all the roots on one side are severed (Heliwell 1985), or if structural root development is asymmetrical (Coutts 1983; Coutts et al. 2000). The danger of uprooting is thus very high when lateral roots of large trees are severed within approximately 1.0–1.3 m of the trunk (Wessolly and Erb 1998). This scenario is extremely critical for urban trees where growing space is restricted and soil conditions are not optimal, resulting in root systems which are often shallow or deformed.

For trees growing in built-up environments, the risk posed by mechanical instability depends largely on the hazard factor and resulting consequences of tree failure. Where human lives and infrastructure are at risk from trees toppling or losing their branches during storms, those trees will be inspected frequently and pruned or removed as necessary. Many guidelines exist to help the arborist decide how to best manage crown cover in urban situations. However, the root system is much more problematic to manage, largely due to the difficulty in investigating it in situ and carrying out experimental studies on this hidden part of trees. To our knowledge, there is little published research on how much root loss a tree can withstand without seriously compromising mechanical stability (Coutts 1983, 1986; Fourcaud et al. 2008), nor at what distance from the trunk digging or trenching can be carried out without increasing the risk of failure. Arborists often use above-ground tree features to specify the dimensions within which root systems should not be damaged. Simple calculations involving branch spread (Bernatzky 1978; Olson and Ray 1979; Schoeneweiss 1982; Tartar 1989; Fazio 1992; Miller and Neely 1993), trunk diameter (Morel 1984, Mattheck and Breloer 1995) and tree height (Miller et al. 1993) are commonly used. Current recommendations as proposed by the British Standard Institute (1989) and Watson (1990) suggest a minimum distance for trenching along one side of the tree of 0.15 m for each 0.025 m diameter at breast height (DBH), whereas Harris et al. (2004) and the American Society of Consulting Arborists (1989) recommend 0.30 m for each 0.025 m DBH (Miller and Neely 1993). Mattheck and Breloer (1995) have also recommended an equation whereby the minimum distance equals the root plate diameter, which in turn is correlated with trunk diameter. Whilst these guidelines may be helpful, advice for arborists concerning the minimum 'safe' distance between a trench and a tree is conflicting. These guidelines have also been developed based on observations of trees and site characteristics after failure occurred and have not been based on sound experimental procedures. As a result, arborists are often in the dilemma of making the decision whether to retain or remove large trees from sites where construction or trenching is carried out close to the tree. Therefore, a rigorous investigation of the influence of root loss through trenching on tree mechanical stability is required. Although a large body of information on tree resistance to windthrow is available in the forestry literature (see review by Peltola 2006), few data exist for urban trees (Bell et al. 1991; Roodbaraky et al. 1994; Mattheck 1998), particularly in tropical areas which are frequently subjected to heavy storms and cyclones.

In temperate forest trees, the relationship between tree resistance to overturning and root morphology has been much elucidated in recent years (Danjon et al. 2005; Dupuy et al. 2005a, b, 2007; Fourcaud et al. 2008; Khuder et al. 2007). Through static bending tests, tree behaviour in a wind storm can be simulated (Achim et al. 2005; Mickovski and Ennos 2003; Cucchi et al. 2004; Nicoll et al. 2005; Stokes et al. 2005; Peltola 2006), although few studies then include an investigation of root architecture (Mickovski and Ennos 2003; Stokes et al. 2007; Dupuy et al. 2007; Khuder et al. 2007). By combining information from bending tests and architectural analysis, it is possible to identify those characteristics influencing uprooting the most. Nevertheless these features depend on species, soil type and planting treatment (Fourcaud et al. 2008; Khuder et al. 2007). A more laborious but practical method for investigating the influence of root system characteristics on tree anchorage is to observe the effect of root removal on resistance to overturning during bending tests (Coutts 1983, 1986, Crook et al. 1997). In urban trees, such a method could be used to determine the effect on anchorage of root removal through trenching. Together with data on root system morphology, the minimum and maximum distances for disturbing and cutting roots of mature trees could be determined.

We carried out a study whereby roots were cut through trenching in the tropical urban species *Eugenia grandis* Wight, grown on sandy clay soil in an urban park in Kuala Lumpur, Malaysia. This species was chosen for the study due to its popularity as an urban landscape tree. Trees which are mature can pose a significant risk to the public, with regard to anchorage during storms, but no study has yet been carried out on anchorage resistance of *E. grandis*. In a series of tests where roots were removed and then winched sideways to failure, we quantified the influence of root loss on tree anchorage. Root morphology was then measured and characteristics correlated with anchorage rigidity. Results are discussed with regard to providing guidelines and advice for the arborist dealing with potential hazard trees in towns and cities.

## Materials and methods

### Site details

The study area was located in the urban park of Taman Tasik Permaisuri (49.4 ha), in the district of Cheras, 15 km south-east of Kuala Lumpur (03°05′81°N″, 101°43′26″E, 79 m above sea level). The site, measuring 31 × 150 m plot with a density of 151 *Eugenia grandis* Wight was established in 1984 as part of the "Greenery and Beautification Programme" conducted by the City Hall of Kuala Lumpur. The plot was situated on a south-west facing slope with an angle of 7–10° and was sheltered from prevailing winds from south-west (SW) and north-east (NE) directions. Generally, Malaysia has two main seasons, the north-east Monsoon (November–March) and the south-west Monsoon (May–September), separated by two relatively shorter inter-monsoon periods. Wind data monitored 25 km away at Subang, showed that the site was subjected to prevailing winds from different directions, depending on the time of year. In May–September, prevailing wind direction was from the SW (mean windspeed of 1.5 $ms^{-1}$), but this changed to NE from November–March (mean windspeed of 1.7 $ms^{-1}$). However, the strongest winds of 35.5 $ms^{-1}$ recorded over a 20 year period came from the NE (300°) and occurred during the inter-monsoon season, in the month of October (Malaysia Meteorological Department, Table 1). Air temperature is monitored at a weather station 8 km away (TUDM Sungai Besi, Kuala Lumpur). The climate is tropical with high temperatures, air humidity and rainfall all year round. Soil at the site was a sandy clay soil and no hard pan or seasonal waterlogging exists, therefore root growth was not restricted vertically.

### Tree selection and experimental layout

In April 2005, a total of 28 trees were randomly selected from a plantation of 20 year old *E. grandis* Wight. Trees were planted in 1984 as seedlings at approximately 4 m intervals. In 2005, stem diameter at breast height (DBH) was 0.21 ± 0.02 m, tree height was 13.80 ± 0.96 m and crown spread was 3.9 ± 0.17 m (means ± standard error). A complete randomised design (CRD) was used to divide trees into four groups. Each group consisted of seven trees and was subjected randomly to three different soil trenching treatments. No trenching was carried out on the control group of trees.

### Tree winching and trenching tests

Tree winching tests were carried out early April 2005 to determine the effect of root loss through trenching on root system anchorage. The tests were carried out when precipitation was maximal, therefore soil moisture content was high. Higher soil moisture content results in lower soil shear strength (Crook and Ennos 1996) therefore failure through winching is more likely to occur in the root system than in the trunk. To remove the confounding parameter of trunk weight and crown area on anchorage (Coutts 1986) the trunk was cut at a height of 2 m above ground level.

The winching tests (Fig. 1) were similar to those carried out in previous studies (Coutts 1986; Crook and Ennos 1996; Papesch et al. 2005; Stokes 1999; Moore 2000; Peltola et al. 2000; Mickovski and Ennos 2003; Cucchi et al. 2004; Nicoll et al. 2005; Stokes et al. 2005). A sling was looped around the trunk of the test tree at a height of 1.8 m. This sling was connected to the winch cable and a hand held winch (maximal force capacity of 32 kN) and attached to the base of an anchoring tree. A pulley attached between the tree and the winch was used to double the winch capacity. A force transducer capable of measuring force up to 20 kN (type K25H–20kN, Scaime S.A., France) was connected between the sling and the winch cable, which recorded tension applied to the winched tree every second using dataloggers (Almemo 2290-8, Ahlborn, Germany). The distance between the test and anchor tree was measured (16.56 ± 1.01 m), along with the azimuth direction in which the tree was pulled.

To quantify the loss of anchorage rigidity through trenching, each tree was winched sideways (in a random direction) before and after trenching. For each test, the tree was pulled sideways to a distance of 0.2 m from its initial position (the amount of cable displaced during the winching test was used to measure the distance of 0.2 m). To

**Table 1** Climatic characteristics (mean windspeed, temperature and rainfall) of the study area

| Mean windspeed | Temperature | Rainfall |
|---|---|---|
| May–September (1.5 $ms^{-1}$) | Annual mean temperature (28.4°C) | Total annual rainfall (2819.4 mm) |
| November–March (1.7 $ms^{-1}$) | Highest temperature (33.8°C) | Annual number of rain days (242 days) |
| Strongest wind (35.5 $ms^{-1}$) | Lowest temperature (23.7°C) | |

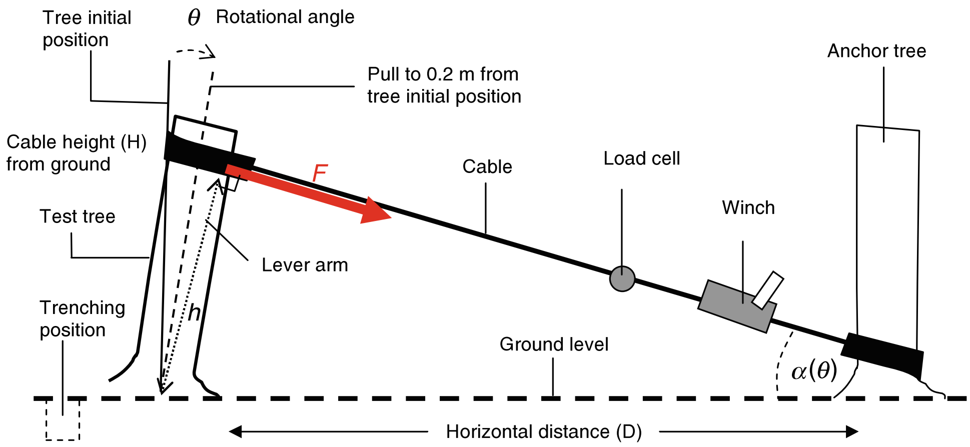


**Fig. 1** Trees were winched sideways and the force necessary was measured using a load cell located between the winch and anchoring tree. A trench was dug at a distance from tree, severing all lateral roots on that side of the tree

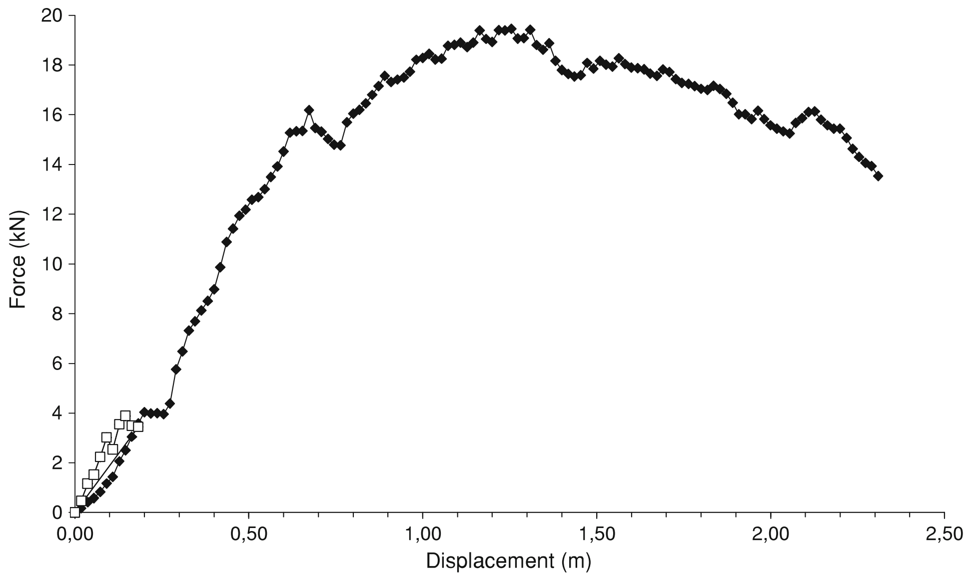


**Fig. 2** A typical force versus displacement graph for a control tree. The initial part of the curve (*white squares*) shows the tree winched sideways to a distance of 0.2 m. The second part of the curve (*black diamonds*) shows the tree winched until failure

test if this deflection was well within the tree's elastic limit, we carried out several loading and unloading tests on extra trees in the plot. The force required to pull the tree 0.2 m sideways was then measured. The tree was released and allowed to return to the vertical. Data were similar each time we winched the same tree to 0.2 m and then released it, before repeating the test (Fig. 2). Therefore we assumed that no plastic damage had occurred. On test trees, a trench (1.0 m deep and 3.0 m long, extending 1.5 m from each side of the trunk) was dug on the counter-winchward (CW) side of each tree using a trenching machine where the major lateral roots were cut off. The CW side of the stem was chosen as roots in this direction are held in tension and account for up to 60% of the total tree anchorage in shallowly rooted species (Coutts 1983, 1986). Therefore, root loss on the CW side of the tree should have a greater effect on anchorage rigidity. Trench dimensions were enough to sever all roots on one side of the tree. For each tree, only one trench was dug at one of three different distances (0.5, 1.0 and 1.5 m) from the stem base. After the trench was made, trees were winched in the same direction until uprooting or stem breakage occurred. In control trees, no trenches were dug and trees were winched to a distance of 0.2 m and then until failure (Fig. 2). Once the winching tests were completed, soil–root plate diameter (perpendicular to the winching direction) and depth were measured and the direction of slope recorded.

To measure root system morphology, trees were then excavated using a mechanical digger. Prior to the excavation, the stump of the study tree was marked according to the pulling direction and north. A 1.0 m deep trench was dug around the tree to sever the remaining roots and the mechanical digger then slowly removed the root system from the soil. Soil was removed from the root systems using a high pressure water jet. All broken roots were collected and tagged and taken together with the root systems to the laboratory for measurement of root morphology.

## Soil measurements

Immediately after each winching test, soil samples were taken to determine if soil water content and bulk density differed between trees and affected the results of the study. For soil moisture analysis, samples ($n = 19$) were taken from three different depths within the soil–root plate (0.05, 0.30 and 0.7 m). Samples were then weighed before drying the soil to a constant mass and weighing again (105°C for 24 h or until no further changes in weight). Soil moisture content was expressed as a percentage (grams of water per 100 g of dry soil).

To measure soil bulk density, a soil corer was used to take samples 70 mm long and 40 mm wide. Three samples were taken from five different locations within the *E. grandis* stand. Soil bulk density was obtained using the core method, where a core ring is pressed or hammered into undisturbed soil to the desired depth and then carefully removed to obtain a known volume of soil. The soil moisture content of each of these samples was measured using the method described above. Therefore, soil bulk density can be calculated for a known volume of soil using Eq. 1:

$$\mathrm{BD} = \frac{\mathrm{Wb} - \mathrm{Wr}}{\pi h d^2/4} \tag{1}$$

where BD is the soil bulk density expressed as g cm$^{-3}$; Wb is the weight of the soil and core ring after oven-drying; Wr is the weight of the core ring; $h$ is the core ring height or depth and $d$ is the core ring diameter.

Mean soil BD was $1.47 \pm 0.01$ g cm$^{-3}$ and did not differ significantly within the *E. grandis* stand. Soil moisture content did not differ significantly either between trees or with depth, with mean values of $35.0 \pm 1.2\%$ at 0.05 m depth, $36.2 \pm 1.6\%$ at 0.30 m depth, and $35.3 \pm 1.7\%$ at 0.7 m depth. Therefore, differences in soil physical properties throughout the site were not considered to influence tree anchorage.

## Measurements of root system morphology

Root system morphology was measured to determine if there was a relationship with tree anchorage rotational stiffness (TARS) and the critical turning moment ($\mathrm{TM_{crit}}$). The shape, size and orientation of all structural roots (defined as any woody root with a diameter > 10 mm) were quantified using techniques similar to those described by Nicoll and Ray (1996), Drexhage and Gruber (1998), Drexhage et al. (1999) and Mickovski and Ennos (2003). Roots <10 mm in diameter were removed from the root systems with secateurs and roots were numbered to aid measurement and data analysis. Measurements were made for all roots in control trees and only where roots had not been cut in test trees. Two types of roots were measured in this study: first order lateral roots (woody roots growing horizontally from the base of the trunk, with a branching angle < 45° from the soil surface) and vertical roots (woody roots originating from the underside of lateral roots, with a branching angle > 45° from the soil surface). In order to investigate the influence of root system architecture and morphology on root system anchorage, the orientation (azimuth) of each first order lateral root was measured together with horizontal ($d_\mathrm{h}$) and vertical ($d_\mathrm{v}$) diameters at four different distances of 0.2, 0.5, 1.0 and 1.5 m from the stem base. For vertical roots, these measurements were made at vertical intervals of 0.3 m from the stem base and data grouped into horizontal distance classes from the stem (0.0–0.19, 0.20–0.49, 0.50–0.99 and 1.0–1.5 m). Root cross-sectional area (CSA) was then calculated at each distance from the tree stem (Eq. 2):

$$\mathrm{root\,CSA} = \frac{\pi d_\mathrm{h} d_\mathrm{v}}{4} \tag{2}$$

The depth and location of each sinker along the first order lateral was also measured. Due to difficulties in excavating all the roots that were broken, damaged or remained in the ground after winching and extraction, therefore it was not possible to measure all roots.

To determine if first order lateral root shape was related to tree anchorage, root eccentricity ($e$) was calculated along with root *CSA*. Each root was considered as an ellipse. Root $e$ was calculated using Eq. 3 (Mickovski and Ennos 2003):

$$e = \frac{\sqrt{d_1^2 - d_2^2}}{d_1} \tag{3}$$

where $d_1$ is the largest root diameter and $d_2$ is the smallest. Values of $e$ close to zero indicate that the shape of the root is almost circular whilst values closer to 1 indicate an elliptical root shape.

## Data analysis

### *Turning moment and root anchorage rotational stiffness*

The turning moment (TM) of root anchorage was calculated by assuming that the tree rotated around an axis that was located at the stem base, the bending of the stem during the pulling test was negligible and the stem was initially perfectly vertical. TM was defined as the product of the force magnitude ($F$) applied to the tree and the lever arm ($h$) that was the distance of the cable from the tree rotation axis (Fig. 1).

$$\mathrm{TM} = Fh \tag{4}$$

The lever arm ($h$) was calculated with regards to the horizontal distance ($D$) between the test and anchoring trees, together with the angle ($\alpha$) between the cable and horizontal directions:

$$h = D \sin \alpha \quad (5)$$

Angle ($\alpha$) between the cable and horizontal directions depended upon the horizontal ($q_x$) and vertical ($q_y$) components of the stem deflection at the point of attachment of the cable:

$$\alpha = \arctan\left[\frac{H - q_y}{D - q_x}\right] \quad (6)$$

Expressing these components ($q_x$) and ($q_y$) with regard to the stem deflection angle ($\theta$) and the height of the cable ($H$), and incorporating into Eq. 6 gives:

$$\alpha = \arctan\left[\frac{H(1-\cos\theta)}{D - H\sin\theta}\right] \quad (7)$$

TARS was then defined as in Eq. 8:

$$\text{TARS} = \frac{\text{TM}}{\theta} \quad (8)$$

*Relative tree anchorage rotational stiffness*

TARS given by Eq. 8 can be used to quantify tree anchorage rigidity before and after trenching. In order to evaluate the change in stiffness after trenching, we defined the relative value of anchorage rotational stiffness (RARS) as

$$\text{RARS} = \frac{(\text{TARS}_0 - \text{TARS}_t)}{\text{TARS}_0} \quad (9)$$

where ($\text{TARS}_0$) was the (TARS) calculated at a stem deflection angle of $\theta = 10°$ before trenching, and ($\text{TARS}_t$) the TARS calculated at the same stem deflection after trenching. RARS was expected to be a positive percentage, i.e. $\text{TARS}_t < \text{TARS}_0$, and was thus considered as an indicator of the stiffness loss after cutting.

*Critical turning moment*

The $\text{TM}_{\text{crit}}$ was defined by incorporating Eqs. 4, 5, and 7 together with the maximum force ($F_{\max}$) recorded during the winching tests when the tree was winched until failure, at the corresponding deflection angle ($\phi_{\max}$).

$$\text{TM}_{\text{crit}} = F_{\max} D \sin\left[\arctan\left(\frac{H(1-\cos\theta_{\max})}{D - H\sin\theta_{\max}}\right)\right] \quad (10)$$

*Root system morphology*

For statistical analysis, each root system was divided into twelve 30° radial sectors with regard to the winching direction, i.e. CW was considered to be at 0°. First order lateral root number, mean and the sum ($\Sigma$) of root CSA were calculated within each sector, at a distance of 0.2 m from the stem. The ratio between first order lateral root CSA and root number was also determined in each sector using root number divided by root CSA. To determine whether slope angle influences root system distribution, each root system was also divided into two 90° radial sectors with regard to slope position (upslope = 0°). This type of analysis allows any preferential directions of root growth to be investigated, and when combined with winching data, can show which part of the root system contributes most to anchorage (Sommerville 1979; Stokes et al. 1995; Nicoll et al. 2006).

Statistical analysis

One-way analysis of variance (ANOVA) and Fisher least significant difference (LSD) tests were used to determine if differences in $\text{TM}_{\text{crit}}$, TARS and root morphological data existed between groups of trees and if differences in soil moisture content occurred with depth and soil BD with site location existed. If trees had been trenched at, e.g. 1.5 m, root characteristics were missing at this distance and these trees were excluded from the analysis of root morphology at 1.5 m. Mean first order lateral root orientation was calculated using circular statistics and Rao's spacing test used to check the null hypothesis that the data were uniformly distributed (Batschelet 1981, Mardia and Jupp 2000, Oriana© 1994–2003 Kovach Computing Services). Normality of data for each treatment was tested using an Anderson–Darling test (data were normally distributed when $P > 0.05$). To examine the directional allocation of root biomass, the centre of mass of all the first order lateral roots, defined as the mean position of the root mass within the root system relative to the stem centre, was calculated using azimuth angles and weighted by CSA (Nicoll et al. 1995; Chiatante et al. 2003, Mickovski and Ennos 2003). The origin of the coordinate system is the centre of the tree trunk, and if the centre of the root CSA is at the origin, root mass is considered evenly distributed around the tree stem. The greater this distance (or mean vector, $r$), the more the roots tend to cluster in a preferred direction. Data presented are means ± standard error.

Stepwise regression analysis was carried out between $\text{TM}_{\text{crit}}$, TARS and individual or combined tree morphological characteristics to determine which parameters were the best predictors of root anchorage. Combined predictors have been shown to be better indicators of pull-out resistance than single predictors (Bailey et al. 2002; Dupuy et al. 2005a; Khuder et al. 2007). The predictors used included $\text{DBH}^2$, $\text{DBH}^3$, $\text{DBH}^4$ and $\text{DBH}^2 \times$ height as these have been shown to be good predictors of $\text{TM}_{\text{crit}}$ (Cucchi et al. 2004; Nicoll et al. 2006), as well as relative root depth (root depth/total root depth), root plate size, lateral root number, root CSA and eccentricity. These regressions were performed for data at different trenching distances from the trunk.

The relationship between Σ root CSA, number of first order lateral roots and the ratio between first order lateral root number and root CSA in each of the twelve 30° radial sectors with TARS before cutting, was explored using Pearson's correlations, considering all trees together.

## Results

### Effect of trenching on anchorage

Failure through uprooting of the root system occurred in 25 trees, whereas three trees broke at the stem–root base. Mean $TM_{crit}$ for all trees, regardless of trenching treatment was 37.1 ± 2.6 kNm. A decrease in $TM_{crit}$ occurred as trenching occurred closer to the trunk, but variability was high, therefore $TM_{crit}$ did not differ significantly between groups of trees (Table 2). Stem DBH, height, crown spread, root plate depth and diameter did not differ significantly between groups of trees (Table 2).

### Effect of trenching on tree anchorage rotational stiffness

The loss of TARS was low in all treatments, ranging from 6 to 13% after trenching (Table 2). RARS was significantly greater when trenching was carried out at a distance of 0.5 m from the trunk compared to distances of 1.0 and 1.5 m (Table 2, $F_{3,24} = 5.17$, $P < 0.001$). No significant differences in RARS occurred between trenching distances of 1.0 and 1.5 m.

### Root system morphology

Although variability in root system morphology was high, a general shape could be observed in the uprooted trees (Fig. 3). Large lateral roots emerged from the stem base and sinker roots descended vertically from the lateral roots and beneath the tree trunk. No taproots were found in these trees. First order lateral root number at the stem base was 26.0 ± 1.4 and this number decreased to only 3.0 ± 0.4 at a distance of 1.5 m, equivalent to a decrease of 88% (Table 3). Most of the first order lateral roots (97%) were found at a depth < 0.3 m beneath the soil surface and only 3% were found at a depth of 0.3–0.6 m. Mean rooting depth for all trees was 0.7 ± 0.3 m, with sinker roots usually located beneath or close to the stem base. The maximum horizontal spread of most major first order lateral roots was 1.5 m from the trunk, with few roots growing beyond this limit. The lateral root ratio with regard to total root number was 0.62.

For sinker roots, the total number per root system ranged from 4 to 31, with a mean of only 17 roots per tree. Of all the trees studied, sinker roots were missing from two root systems, hence these systems were relatively shallow (maximal depths of 0.3 and 0.4 m). 88% of the total sinker roots occurred within a distance < 0.5 m from the stem base, and 32% of these roots were located at the stem base. The maximum depth of these sinker roots located close to


**Fig. 3** **a**, **b** Excavated root systems of two 20 year old *Eugenia grandis* Wight trees

**Table 2** Critical turning moment ($TM_{crit}$) and relative anchorage rotational stiffness (RARS) before and after cutting in all trees (data are means ± standard error)

| Parameter measured | Trenching distance from stem (m) | | | |
|---|---|---|---|---|
| | 0.5 | 1.0 | 1.5 | Control |
| $TM_{crit}$ (kNm) | 32.8 ± 3.6$^a$ | 38.6 ± 3.1$^a$ | 41.7 ± 8.7$^a$ | 36.0 ± 3.6$^a$ |
| RARS (%) | 13 ± 3$^a$ | 6 ± 1$^b$ | 9 ± 2$^b$ | – |

Where letters in superscript differ, $P < 0.05$

**Table 3** General characteristics of major structural roots (diameter > 10 mm) of *Eugenia grandis* Wight in the study area by distance class: a) lateral roots, and b) sinker roots (data are means ± standard error)

| Parameter measured | Distance class from stem (m) | | | |
|---|---|---|---|---|
| | 0.2 | 0.5 | 1.0 | 1.5 |
| (a) Lateral roots | | | | |
| No of roots | 26.0 ± 1.4$^{a}$ | 22.0 ± 1.6$^{b}$ | 8.0 ± 1.1$^{c}$ | 3.0 ± 0.4$^{c}$ |
| Mean *CSA* (mm$^2$) | 170.0 ± 10.6$^{a}$ | 92.2 ± 7.7$^{b}$ | 52.3 ± 5.9$^{c}$ | 44.8 ± 7.7$^{c}$ |
| Mean total *CSA* (mm$^2$) | 4723 ± 233$^{a}$ | 1973 ± 184$^{b}$ | 427 ± 66$^{c}$ | 117.8 ± 19.2$^{c}$ |
| Mean eccentricity (*e*) | 0.7 ± 0.02$^{a}$ | 0.5 ± 0.02$^{b}$ | 0.4 ± 0.02$^{c}$ | ND |
| Root plate diameter (m) | – | 2.08 ± 1.60$^{a}$ | 2.47 ± 0.29$^{a}$ | 2.01 ± 0.18$^{a}$ |
| | 0.0– 0.19 | 0.20– 0.49 | 0.50–0.99 | 1.0–1.5 |
| (b) Sinker roots | | | | |
| Maximum depth (m) | 0.70 ± 0.02$^{a}$ | 0.80 ± 0.03$^{b}$ | 0.70 ± 0.05$^{a}$ | ND |
| Mean no of sinker roots | 8.0 ± 0.8$^{a}$ | 7.1 ± 0.8$^{b}$ | 3.7 ± 0.8$^{c}$ | 1.5 ± 0.5$^{c}$ |
| Mean *CSA* (mm$^2$) | 73.2 ± 6.9$^{a}$ | 59.1 ± 7.7$^{a}$ | 55.3 ± 16.5$^{a}$ | ND |
| Mean total *CSA* (mm$^2$) | 636.8 ± 73.6$^{a}$ | 400.8 ± 47.2$^{b}$ | 203.3 ± 52.5$^{c}$ | ND |

Where letters in superscript differ, $P < 0.05$

*ND* not enough data available

the stem was 0.81 ± 0.09 m. Mean sinker root size, mean sinker CSA and rooting depth decreased significantly with distance along the horizontal roots (Table 3). No significant relationship existed between the mean total number of sinker roots and any stem size variable.

The mean CSA of first order lateral roots decreased significantly from 170.0 ± 10.6 mm$^2$ at a distance of 0.2 m from the trunk to 44.8 ± 7.7 mm$^2$ at 1.5 m from the stem ($F_{3,98} = 46.6$, $P < 0.001$, Table 3). The mean total CSA of all first order lateral roots also decreased significantly with distance (Table 3, $F_{3,98} = 150.77$, $P < 0.001$), with the highest value of (4,723 ± 233 mm$^2$) at a distance of 0.2 m from the stem base.

Mean total root CSA at 0.2 m from the stem regressed significantly with DBH, although R$^2$ was low ($y = 34.6x - 474$, $R^2 = 0.26$, $P < 0.01$). However, no significant relationships were found between mean total root CSA and any other root or shoot variable. When mean stem CSA was regressed against total root CSA, a significant positive relationship was found, although $R^2$ was low ($y = 0.152x + 2312$, $R^2 = 0.36$, $P < 0.001$).

## Lateral root directional analysis

Mean azimuth when all first order lateral roots were considered together was 7.0 ± 11.9° and these roots were significantly clustered in this direction, but with a bimodal distribution towards the NE and NW ($r = 0.6$, Rao's spacing test: $P < 0.01$, Fig. 4a). When root CSA was taken into consideration, the centre of root mass shifted slightly to a mean azimuth of 16.3° ± 10.3 ($r = 0.64$, Rao's spacing test: $P < 0.01$) indicating significant clustering of the root system (Fig. 4b), with mean root CSA clustered towards the NE. Although this shift is relatively small, the result was found to be significant ($F_{1,56} = 4.03$, $P = 0.05$) when root CSA was taken into account.

## Root eccentricity

Root vertical *e* decreased significantly with distance from the tree trunk (Table 3, $F_{2,81} = 43.5$, $P < 0.01$), with the highest value of 0.7 ± 0.02 at a distance of 0.2 m from the stem base, indicating that these roots had adopted an elliptical form. However, at a distance of 0.5 and 1.0 m

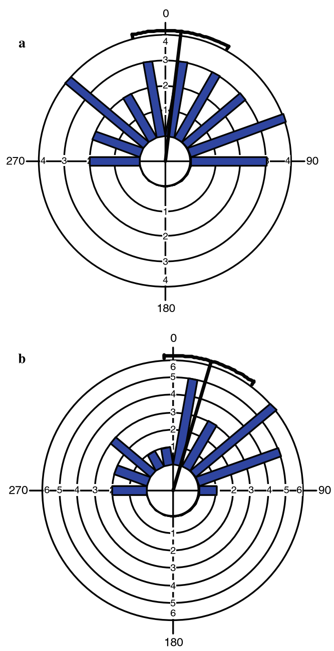


**Fig. 4** **a** Significant clustering of first order lateral roots towards an angle of 7.0 ± 11.9° (*solid line*) occurred when the mean azimuth was calculated with regard to north (where winching direction = 0°). **b** When first order lateral root CSA for all trees with regard to winching direction was determined, significant clustering of first order lateral roots occurred towards an angle of 16.3 ± 10.3°. Each *bar* indicates the mean orientation of first order lateral roots for each tree and the solid line indicates the direction of clustering of center of CSA for all trees

**Table 4** Predictors and combinations of predictors which regressed significantly (x) with $TM_{crit}$ within each treatment ($R^2$ was > 0.5 and $P < 0.05$ in each case)

| Predictor | Trenching distance from stem (m) | | | |
|---|---|---|---|---|
| | 0.5 | 1.0 | 1.5 | Control |
| $DBH^2$ | – | – | – | x |
| $DBH^3$ | – | – | – | x |
| Max. root depth | – | – | – | x |
| Relative max. root depth | – | – | – | x |
| No. of laterals | – | – | – | x |
| DBH, height | – | – | – | x |
| DBH, relative max. root depth | – | – | – | x |
| DBH, no. of laterals | – | – | – | x |
| DBH, root plate diameter | – | – | x | x |
| $DBH^2 \times$ height | – | – | x | x |
| Height, max. root depth | – | – | – | x |
| Height, root plate diameter | – | – | x | – |
| Max. root depth, root plate diameter | – | – | x | x |
| Max. root depth, no. of laterals | – | – | – | x |
| Relative max. root depth, No. of laterals | – | – | – | x |

**Table 5** Predictors and combinations of predictors which regressed significantly (x) with TARS within each treatment ($R^2$ was > 0.5 and $P < 0.05$ in each case)

| Predictor | Trenching distance from stem (m) | | |
|---|---|---|---|
| | 0.5 | 1.0 | 1.5 |
| $DBH^2$ | x | – | – |
| $DBH^3$ | x | – | – |
| $DBH^2 \times$ Height | x | – | – |
| Max. root depth | – | – | x |
| Max. root depth, root plate diameter | – | – | x |
| Max. root depth, height | – | – | x |
| Max root depth, DBH | – | – | x |
| Relative root depth | – | – | x |
| Relative max. root depth, Height | – | – | x |
| Mean CSA at 0.2 m, max. root depth | – | – | x |

from the trunk, roots were significantly more circular in shape (Table 3) as compared to roots at 0.2 m from trunk. No significant relationships were found between root *e* and any other tree parameter.

## Relationship between root system anchorage and morphology

When $TM_{crit}$ was regressed against various root and shoot morphological characteristics for control trees, highly significant relationships were found with stem $DBH^2$, $DBH^3$, and rooting depth ($P < 0.001$, Table 4). For trees where roots had been cut at 1.5 m, RARS best regressed with rooting depth and a combination of predictors of tree height, root plate diameter and DBH ($R^2 > 0.8$, $P < 0.05$; Table 5). Surprisingly, no significant relationships existed between any variable and RARS in trees where roots had been cut at 1.0 m. In trees where roots had been cut at a distance of 0.5 m from the stem, DBH parameters and combination of $DBH^2 \times$ height were best regressed with RARS, although $R^2$ was not high ($R^2 = 0.58$ and 0.53). No significant relationships existed with any other shoot or root variable.

No significant correlations were found between Σ root CSA in each of the twelve 30° radial sectors and TARS before cutting. However, root number was negatively correlated with TARS in one sector only: 16–45°, i.e. on the CW side of the tree ($R = -0.43$, $P = 0.030$, Fig. 5a). A negative correlation also existed between TARS and the ratio of lateral with root number with *CSA* in the CW sector 346–15° ($R = -0.38$, $P = 0.05$, Fig. 5b) and the WW sector 106–135° ($R = -0.47$, $P = 0.014$, Fig. 5b).

## Discussion

The effect of trenching on TARS was slight, with a loss of only 13% when roots were cut at a distance of 0.5 m from the tree trunk and surprisingly, no significant differences in $TM_{crit}$ were observed with regard to trenching distance from the tree stem, possibly due to the variability observed in the data. Nevertheless, although trenching appeared to have little direct influence on tree mechanical stability, by analysing the relationships between $TM_{crit}$ or TARS and tree morphological characteristics, we were able to determine several mechanisms involved in root anchorage.

The relationship between root anchorage and various shoot and root parameters have often been used to determine which are the best characteristics to predict uprooting resistance in trees (Dupuy et al. 2005a, 2007; Nicoll et al. 2006; Peltola 2006; Khuder et al. 2007). We found many significant regressions between $TM_{crit}$ and TARS and different variables in the control group of trees, but the most significant relationships were with a combination of the parameters DBH or tree height and root system depth. As most sinker roots were located close to the trunk, these roots would not be damaged through trenching, and could therefore continue to function as major component of anchorage (Mickovski and Ennos 2003), even though the amount of biomass allocated to these roots was significantly less than that in the lateral roots (Table 3). Fourcaud et al. (2008) showed through numerical modelling of tree anchorage in a saturated clay soil, that if a taproot is present, the length ratio of this taproot with the length of

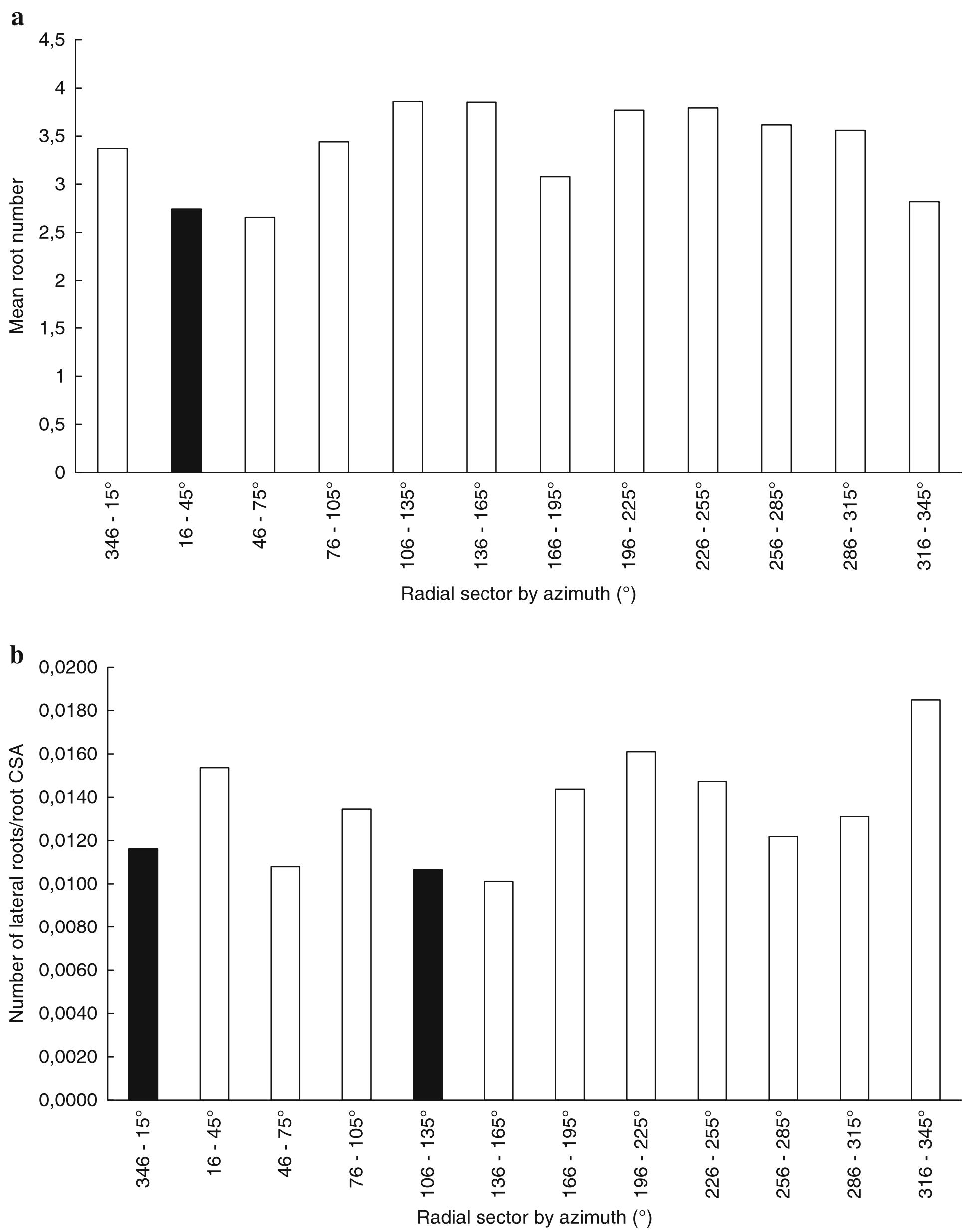


**Fig. 5** Relationship between **a** mean root number and **b** ratio between first order lateral root number and CSA with bending stiffness before cutting in each of the twelve 30° radial sectors. The counter-winchward direction was considered to be at 0°. *Black bars* indicate sectors where Pearson's correlations were significant ($P < 0.05$)

the zone of rapid taper (ZRT) is also an important component of anchorage. The ZRT is the zone of major growth in lateral roots adjacent to the stem base (Wilson 1975) and tapers quickly so that eccentrically shaped roots rapidly become more circular. In trees in our study, sinker roots were clustered together underneath the tree stem, therefore could be considered as acting like a single, large taproot, which act as the dominant component of anchorage. If the length ratio between this taproot and the length of the ZRT is >1, Fourcaud et al. (2008) suggest that the taproot is the dominant component of anchorage, therefore, trenching lateral roots will have little effect on anchorage. In *E. grandis*, the ZRT could be considered as being shorter than 0.5 m, whereas maximum sinker depth was 0.7 m, also located underneath the trunk.

In trees where trenching had been carried out, root loss during excavation of the root systems may have also influenced the results as no significant relationships between $TM_{crit}$ or TARS and root characteristics were found. However, when trenching was carried out at distances of 0.5 or 1.0 m from the tree stem, no significant relationships were found between $TM_{crit}$ and any other parameter, nor were any relationships found between TARS and any root system variable, including depth. When trenching was performed at a distance of 1.5 m from the trunk, a combination of the parameters root system depth and root plate diameter or tree height were the best predictors of both $TM_{crit}$ and TARS and several significant relationships were found between TARS and DBH, tree height and root system width and depth. Therefore, when roots were cut through trenching at distances of less than 1.5 m, something happened to the anchorage mechanism which prevents uprooting resistance being predicted from root system parameters. In our study, we could not know if the longest lateral roots were cut, as trenching would have damaged these roots which were left in the soil, but it would seem likely that this had occurred.

It was surprising that no significant regressions were found between root CSA and $TM_{crit}$ or TARS, even in the control trees, where significant relationships were more numerous. Root CSA has been considered as playing a major role in tree anchorage, particularly in roots close to the stem (Nicoll and Ray 1996; Coutts et al. 2000; Nicoll 2000; Chiatante et al. 2003; Danjon et al. 2005). Nevertheless, significant negative correlations were found between TARS before trenching and the number of first order lateral roots in the CW sector at 16–45° and the ratio between first order lateral root number and CSA in the neighbouring sector (346–15°) and opposite side of WW sector (106–135°). No relationship occurred between TARS and root CSA in any sector, but a significant result was found between TARS and the ratio of number of lateral roots and root CSA, which suggests that an increase in root *CSA* on the CW side (side held in tension) of the tree increases anchorage; however, at the expense of lateral root number. These results are partly contrary to those found by Coutts (1983), who showed that the thickness of lateral roots on the WW side (side held in compression) of the tree will influence positively anchorage rigidity, whereas on the CW side, an increase in root number will augment overturning resistance (Stokes et al. 1995).

When all the azimuths of all first order lateral roots were analysed, it was found that lateral roots were significantly clustered with a bimodal distribution towards the NE and NW. However, when the centre of mass of all first order lateral roots was calculated, using azimuth angles and weighted by CSA, the mean azimuth towards which roots were clustered was slightly shifted towards 16.0°. This clustering of lateral roots did not affect anchorage, as also found by Mickovski and Ennos (2003) studying *Pinus peuce* Griseb. In our study, both sets of results indicate that there is an increased allocation of root biomass on the northern side of the tree. Asymmetric structural root growth in temperate trees is related to genotype (Nicoll et al. 1995), competition between roots for nutrients early on in their development (Coutts 1987), poor planting conditions (Taylor and Gardner 1963; Coutts et al. 2000; Lindström and Rune 1999) and mechanical loading, e.g. unilateral wind loading (Stokes et al. 1995; Mickovski and Ennos 2003) or slope orientation (Watson et al. 1995; Chiatante et al. 2003; Di Iorio et al. 2005; Nicoll et al. 2006). Radial growth of roots is also influenced by mechanical stresses, which are usually higher at the base of the tree, thus resulting in thicker roots in this zone (Nicoll and Ray 1996). Our results suggest therefore that the asymmetric root systems in *E. grandis* trees may in part be due to the mechanical loading from the northerly prevailing wind direction during the monsoon season. However, the trees were also growing on a slight slope of 7–10° and preferential root clustering corresponded to the upslope direction. Therefore, the combination of dynamic and static stresses, which has already been shown to result in amplified plant response to mechanical loading (Berthier and Stokes 2006; Khuder et al. 2006), may have augmented root growth on the northern side of the tree. The results of our study are comparable to those of Nicoll et al. (2006) who examined root system symmetry of 40 year old Sitka spruce (*Picea sitchensis* Bong. Carr.) grown on a steeper slope (26–33°), where roots were distributed unevenly around the trunk, growing predominantly up and across the slope towards the windward direction. However, Di Iorio et al. (2008) showed that soil type is also an influencing factor for root directional growth on slopes.

Not only does mechanical stress lead to an increase in root radial growth, but also contributes towards eccentric secondary growth (Nicoll and Ray 1996; Stokes et al. 1998; Mickovski and Ennos 2003). Root *e* was highest close to the trunk in the *E. grandis* trees studied, with most growth along the vertical bending axis. However, at a distance of 0.5 and 1.0 m from the stem, root eccentricity was significantly less elliptical, and more significantly circular in shape. Radial eccentricity has been linked to the distribution of strain throughout the root system during mechanical loading (Ennos 1993; Nicoll and Ray 1996; Fourcaud et al. 2008). Roots often have greater thickening on the upper sides where strain is high, producing a shape comparable to a “T-beam” close to the trunk on leeward side of the tree or “I-beam” shapes further away from the trunk, particularly on the windward side where roots experience tension and bending (Nicoll and Ray 1996; Mickovski and Ennos 2003; Di Iorio et al. 2007). Such changes in root CSA can resist bending resistance within the soil more than any other shape with a similar *CSA* (Nicoll 2000) and further increase rigidity of the root soil plate (Nicoll and Ray 1996).

Our study showed that in terms of TARS and $TM_{crit}$, tree mechanical stability was not greatly affected by trenching in *E. grandis* trees, even when roots were severed at 0.5 m from the trunk. As maximal rooting depth was a good predictor of anchorage and most sinkers were located close to the trunk, the severing of lateral roots probably had little effect on tree stability, even though the amount of biomass allocated to lateral roots was significantly greater than that in the sinker roots. However, the fundamental root anchorage mechanism was disrupted in that overturning resistance could not easily be predicted from root system characteristics when trenching occurred at 0.5 or 1.0 m. Fourcaud et al. (2008) suggest that in clay soils, the longest lateral roots, if longer than the taproot, determine the size of the soil–root plate, a major component of tree anchorage, therefore this plate should not be damaged. If these main lateral roots are removed or cut, then the plate size will be mainly defined by the depth of the taproot, i.e. no longer sensitive to the removal of laterals. However, the same authors show that uprooting mechanisms also depend largely on soil mechanical properties. Hence, it is difficult to give advice to the arborist concerning the minimal distance to be left between the stem and the trench, as this will differ depending on species, soil conditions and tree vigour. From our study, we suggest that rooting depth and root plate size are the most important criteria to consider before trenching is carried out. Root plate radius is correlated to stem radius and this simple relationship can therefore be adapted to many species in different environments (Mattheck and Breloer 1995). Nevertheless, the effect of trenching may not be perceived immediately, and there is also a high risk of pathogens entering the severed roots and causing decay in the tree, thus decreasing mechanical stability further. More similar studies need to be carried out on different species in a variety of urban conditions, in order to elucidate further the effect of root loss on trees growing in the built-up environment.

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