DYNAMICS AND AERODYNAMICS OF DECIDUOUS URBAN TREES

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by

Hilary Jane Roodbaraky, B.Sc

Department of Civil Engineering
University of Nottingham

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Abstract

Strong winds cause a great deal of damage to trees, and these falling trees inevitably damage property, communication lines and may even cause fatalities. This thesis presents an investigation into tree stability.

The following genera were found to be most commonly occurring in extensive surveys in the south of England following the strong winds of October 1987: *Acer* (Maple), *Aesculus* (Horse chestnut), *Fagus* (Beech), *Quercus* (Oak) and *Tilia* (Lime). The *Fagus* and *Tilia* were found to be more prone to uprooting whilst the *Aesculus* and *Quercus* were more susceptible to crown breakage.

Trees of all sizes were observed to suffer crown damage and/ or uprooting. However, with the exception of trees above 30 m in height, trees of every height were also found undamaged by the high winds. Smaller trees (5 m) were rarely recorded in the storm damage surveys, but this was thought to be due to the smaller amount of damage caused by them rather than being representative of the actual number damaged.

The literature review revealed little information on broadleaf trees but suggested that uprooting was a dynamic process. Observations of a *Platanus* (Plane) in high winds revealed natural frequencies of 0.25 Hz whilst the tree was in leaf and 0.8 Hz when it was without leaves. Damping coefficients of 0.25 and 0.08 respectively, were also measured. High wind speeds were recorded whilst the tree was without leaf, but greater tree displacement was recorded at the lower wind speeds when the tree was in full leaf.

Forced oscillation experiments produced similar values of natural frequency and damping. Additionally, with static loading experiments to determine load/ deflection curves, values of drag coefficients were determined. These were calculated to be 0.8 whilst the tree was in leaf and 0.2 without leaves. The value for the tree in leaf is similar to those determined for conifers by Mayhead (1973a).

The uprooting of stumps showed self-seeded trees to be more stable than those planted in soil pits which had developed pit-bound roots. Uprooting by winching at heights of 0.5 m - 1 m, enabled these comparative conclusions to be drawn, but was thought not to realistically simulate the uprooting process of the wind acting on the trees' crown.

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Nomenclature

Latin name	English name
Abies grandis	Grand fir
Acer	Maple
Acer platanoides	Norway maple
Acer pseudoplatanus	Sycamore
Acer saccharinum	Silver maple
Aesculus	Horse chestnut
Aesculus hippocastanum	Horse chestnut
Betula	Birch
Betula pendula	Silver birch
Betula verrucosa	European white birch
Carpinus	Hornbeam
Carya glabra sweet	Pignut hickory
Castanea	Sweet chestnut
Cedrus	Cedar
Ceratanin siliqua	Carob
Crataegus	Hawthorn
Fagus	Beech
Fagus sylvatica	Beech
Fraxinus	Ash
Gingko biloba	Gingko
Larix decidua	Larch
Liquidamber styraciflua	Sweet gum
Liriodendron tulipifera L.	Tulip tree
Malus	Apple
Malus 'John Downie'	Apple variety 'John Downie'
Malus sylvestris	Crab apple
Picea	Spruce
Picea abies	Norway spruce
Picea sitchensis	Sitka spruce
Pinus	Pine
Pinus contorta var. latifolia	Lodgepole pine
Pinus resinosa	Red pine
Pinus strobus L.	White pine
Pinus sylvestris	Scots Pine
Platanus	Plane
Platanus acerifolia	London plane
Populus	Poplar
Populus tremula	Aspen
Prunus	Cherry/ Plum
Pseudotsuga menziesii	Douglas fir
Quercus	Oak
Quercus alba L.	White oak
Quercus cerris	Turkey oak
Quercus ilex	Holm oak
Quercus macrocarpa	Burr oak
Quercus petraea	Sessile oak
Quercus robur	English oak
Quercus X hispanica 'Lucombeana'	Lucombe oak
Sorbus	Rowan/ Whitebeam
Sorbus aria.	Whitebeam
Tilia	Lime
Tilia europea	European lime
Tilia platyphyllos	Larged-leaved lime
Tilia vulgaris (syn. Tilia x europea)	Common lime (European)
Tsuga heterophylla	Western hemlock
Ulmus	Elm

Notation

$\bar{j}$	: mean
$\bar{v}$	: mean wind velocity
a	: amplitude of resonant peak
A	: building area presented to the wind
b	: amplitude of spectrum at the same frequency if there were no resonant peak
β	: angle between roots
B	: resistive bending moment
c	: damping coefficient
C_D	: drag coefficient
C_{DR}	: drag coefficient at reference wind velocity
δ	: logarithmic decrement
D	: drag
df	: degrees of freedom
e	: radius of the trunk at base
E	: mean modulus of elasticity
ϕ	: phase angle difference
F	: applied force
f	: root length proximal to the fulcrum
γ	: dimensional constant
g	: distance of force from the fulcrum
G	: standard deviation
h	: radius of trunk at specified height
H	: radius of curvature of the base of the stem
K	: coefficient in the simplification of equation 5.3
k	: spring constant of stem
λ	: damping
M	: mass
m	: power to which the velocity must be raised to vary proportionally to the tree deflection
M_c	: mass of crown
n	: frequency
N	: number of observations
n_p	: peak frequency
P_c	: breaking stress of green timber
θ	: amplitude of tree deflection
Q	: trunk taper parameter
ρ	: air density
r	: radius of the trunk at point of loading
σ	: root mean square of wind velocity
s	: stiffness
$S(n,Z)$	: power spectral density
T	: t-statistic of t-test
t	: time
u	: length of lever arm

U	:	turning/ uprooting moment
V	:	wind velocity
V_R	:	reference wind velocity (10 ms^{-10})
w	:	length of rod
W	:	sway period of trees
ω_n	:	natural radial frequency of oscillation
x	:	displacement
$^xL_v(Z)$	:	streamwise turbulence length scale
y	:	diameter
$Y\cos(\omega t)$	:	periodic oscillating force
Z	:	height above ground level

Chapter 1

Introduction

1.0 The background

Storms have caused havoc in the British Isles on many occasions in the past. Those of exceptional ferocity occurred in 1928, 1952, 1953, 1957, 1961, 1962, 1968, 1976, 1987, 1989 and 1990 (The Meteorological Office, 1990). Strong winds are generally widespread throughout Britain, though specific storms have been localised. The gales of 1961, for example, were concentrated in the north of Scotland, whilst those of 1987, were concentrated primarily in the south east of England. The damage caused by these high winds has also been seen to vary, sometimes causing extensive damage to forests and trees, to buildings, or sometimes causing flooding in coastal areas.

The storm of 1987, though not necessarily of greater intensity or ferocity than any of the others listed above, caused the most dramatic repercussions. The high winds were centred on the densely populated south east of England. A significant amount of damage was caused to the tree population of this area, with many trees being uprooted or incurring crown mutilation. Though this itself being devastating, the damage which the windblown timber caused to buildings and to the communication network was exceptional. It virtually brought the stock market to a halt, and generally caused great disruption to the Capital and Home Counties. As a result public awareness and concern over the value and safety of amenity trees was greatly increased.

Many questions were raised in the wake of the storm. These, listed below, form the initial objectives of the research.

Was it the oldest trees that fell?, or the tallest?

Was any particular genus or species more vulnerable than another?

Are tree location and soil type important factors?

Can one tell if a tree will uproot in strong winds?

What are the mechanisms of the uprooting process?

1.1 The Research Proposal

Research was thus commenced at Nottingham University under an SERC grant following a proposal to investigate some of the above questions.

Preliminary investigations revealed that the conifer and its behaviour in high winds had been the topic of research for many years with the Forestry Commission and other forestry groups, the reason being to try to increase and improve timber production in the more exposed and less favourable areas of the country, by different planting and management regimes. The broadleaf tree however, not thriving so well in the harsher conditions of the North, is rarely grown commercially in areas of frequent high winds and is therefore the subject of much less wind-related research.

In more southerly areas however, broadleaf trees form a higher proportion of the tree population, some growing naturally and others planted for urban amenity, as windbreaks and within hedges and on roadsides. It was decided that the research be primarily concerned with the 'broadleaf' tree, though it was hoped also to draw similarities/ differences with the research already undertaken on conifers.

It was also decided that research be concentrated on the isolated tree. 'Isolated' is used here to describe trees not growing in woodland, but those growing singly, in streets, avenues or in small groups. This was selected for two reasons; the first being that it models the tree growing within the urban environment, where quite apparently, it can do most damage; and secondly the analysis of conditions incident on one tree must be far simpler and more reproducible than if complications were added by increasing numbers of trees.

Even with the prime objective defined as the isolated broadleaf tree, the scope for research still remained vast. The issues involved in the tree system are not solely concerned with the tree, but also with its interaction with the climatic conditions, and the aerial and ground environment. Biological variation should be expected between species and also between each individual specimens.

All the factors initially thought to be involved in tree stability are summarised in Figure 1.1. The significance of each factor and its interaction and relationship with other factors was of prime concern throughout this research.

Trees have adopted various forms during their evolution, suited to the differing biological and physical conditions encountered in their natural habitat.

Each individual specimen also has the same ability to adapt in response to changes in its immediate environment. Generally the tree adopts a form to maximise photosynthate production within its structural capabilities. That is, they grow to withstand a degree of harsh conditions, though not necessarily with a sufficient safety margin to withstand a 50 or 100 year return wind speed, - a prerequisite for an engineering structure.

This phenomenon, the ability to adapt, highlights an important caution which must be born in mind throughout this research. That is, the tree is a living organism and may not always conform to engineering ideals. Trends in the observations should not be discredited by the apparent erratic behaviour of an individual specimen.

1.2 The Thesis

A full literature review (Chapter 2), revealed the limits of relevant research, Most examples were drawn from the coniferous trees, highlighting a clear lack of similar knowledge of the broadleaf tree.

The storm of 1987 had allowed the collection of data concerning many aspects of tree fall. Two detailed surveys had been undertaken, one by the Forestry Commission and the other co-ordinated by the Royal Botanic Gardens at Kew, funded by the Countryside Commission. Each survey contained valuable information on many aspects of tree fall. It was hoped that by comparing the two surveys further information could be generated (Chapter 3). Together these two surveys contained information on over 4500 trees. The two surveys were also compared with a third database, from Essex County Council. This database held records of all the trees present on land owned by the County Council, providing a much greater tree population for comparison (over 34000 trees).

The storms of 1990 provided an excellent opportunity to experience storm damage first hand. Tree casualties both in Aberdeen and in the south west of England were observed. Chapter 4 presents a much smaller survey than those described in Chapter 3, due limited time and manpower. However these surveys were exceptionally useful in highlighting the validity of, and the practical difficulties involved in the actual surveying and data recording processes. The merits of surveying tree fall are thus addressed at the end of Chapter 4.

With the information gleaned from both the literature review and the storm damage surveys, the direction of practical research was planned. Liaisons were formed with the Research Divisions of the Forestry Commission, and using their experience with coniferous trees, experimental procedures and apparatus were designed. Experimentation investigated the horizontal trunk displacement of trees both in the wind (Chapter 5) and by artificial loading (Chapter 6). The literature review indicated that the dynamic behaviour of the tree was important in the uprooting process. Consequently this was also studied, both as the trees response to the wind and to the artificial loading. At the end of Chapter 6, these observations were combined to calculate the drag coefficient of a broadleaf tree, which could then be compared with those of conifers found in the literature review. A video showing both forced oscillation experiments and tree movement in the wind was made. Although no numerical data was extracted from the video, it clearly shows the scale of tree displacement which occurred in the wind, and during the forced oscillation experiments. The video may also serve to clarify experimental technique, should anyone require to replicate the experiment. The video is available from Dr. C J Baker, Department of Civil Engineering, Nottingham University, University Park, Nottingham, NG7 2RD. Experimental data is also available from this address.

A further area of experimentation was in the actual uprooting of tree stumps. Chapter 7 gives details of the uprooting of two series of trees, one of which were also the subject of earlier trunk displacement experiments. A further and important difference between the two series of trees uprooted, was that one set of trees were self sown, and the other were planted for amenity purposes. The uprooting process is also shown on the above mentioned video.

All the results are then drawn together and conclusions made in Chapter 8. These conclusions also confirm the novelty of the research and subsequently many suggestions are presented for future researchers to pursue.

Throughout the thesis, to prevent any misunderstanding or confusion, Latin (or scientific) names have been used for the tree genera or species. A common English name for each species is listed in the Nomenclature and is given following the Latin name on its first appearance in the text.

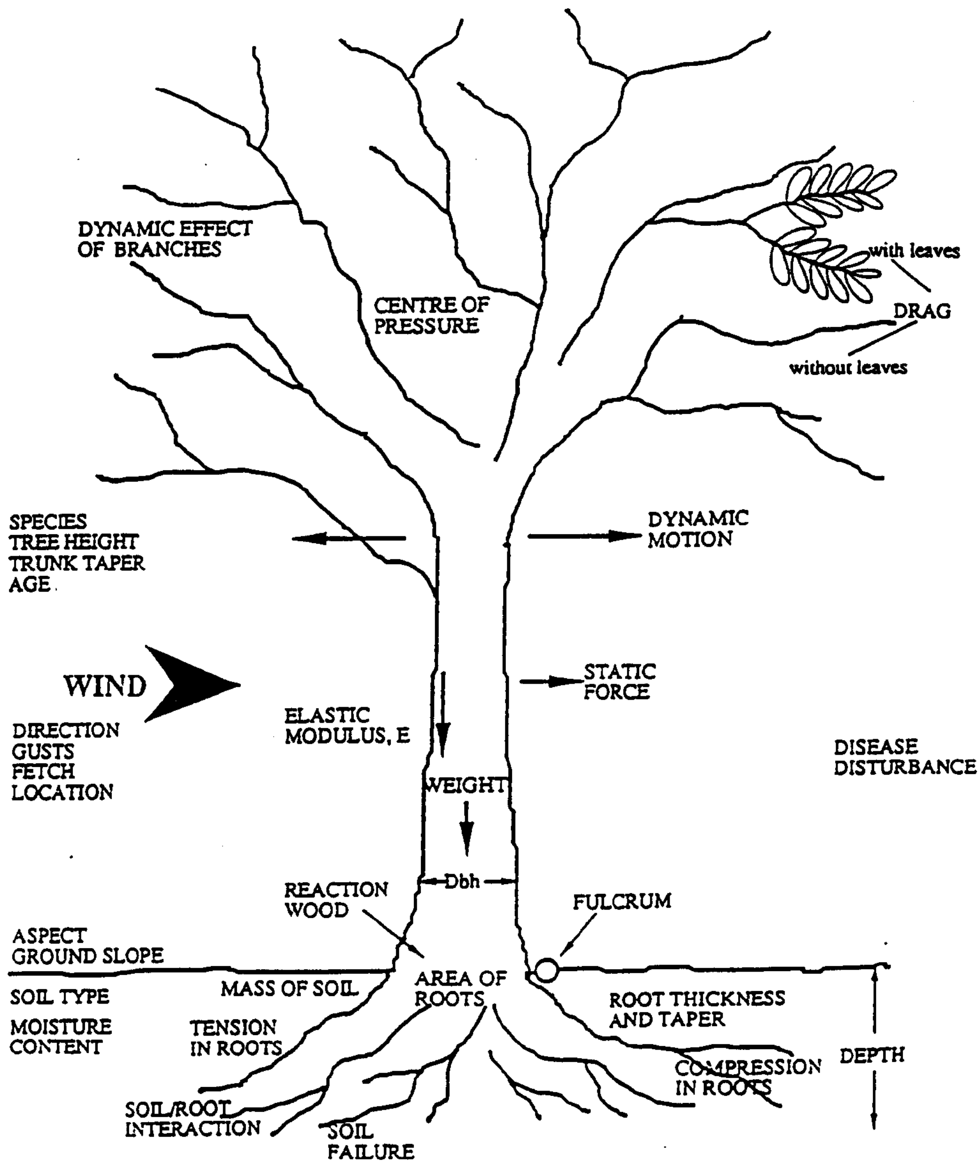


Figure 1.1 Summary of factors involved in tree stability

Chapter 2

Literature Review

2.0 Introduction

Literature concerned with tree fall in high winds is diverse and widespread. The behaviour of conifers in winds has been the topic of research for many years for the Forestry Commission and other forestry groups, their aim being to improve and increase timber production particularly in the more exposed and less favourable areas by different planting and management regimes. The broadleaf tree has been the subject of much less wind-related research. However, much of the work on conifers will undoubtedly relate to broadleaf trees and prove very valuable, though differences should be expected.

It immediately became apparent that tree stability is a very complex issue. Many different factors appear to be important. These include the tree itself, and the surrounding aerial and subterranean environments. Research concerned with the significance of each factor, its interaction and relationship with other factors form the basis of this literature review.

The tree is first considered as a simple plank of wood subjected to bending forces (Section 2.1). This is followed by a discussion of tree stability which includes a review of experiments (Section 2.2), on static loading (Section 2.2.1), wind tunnel testing (Section 2.2.2) and dynamic loading (Section 2.2.3). The growth and adaptation of trees to withstand external forces is then discussed (Section 2.3). The contribution to stability of the roots is also considered with regard also to varying soil types (Section 2.4). Points arising from this literature review are then highlighted (Section 2.5), and used to suggest various lines of study.

2.1 The Tree Structure

Tree structure has been closely investigated, in particular the height to which a tree can grow and support its own weight (Pugsley 1988). McMahon (1973 - cited in King 1986) concluded that record sized trees averaged only about one quarter of the theoretical height to which trees would buckle under their own weight. King (1981 cited in 1986) calculated much smaller safety margins for densely grown *Populus tremula* (Aspen). These calculations considered only the resistance to gravity forces generated by bending moments and did not consider wind forces.

Wind incident on trees may not always cause failure by uprooting. It may be that the stress in the trunk causes the trunk to snap before the turning moment exceeds that necessary to uproot the tree. The structure and strength of the trunk therefore required investigation.

The conifer is a relatively simple shape with a single stem which tapers from the base to the top. In analysis this may be considered similar to a beam fixed at the base which is subject to a force at the top, inducing bending. If the beam is to present an equal resistance to bending along its entire length it requires, at any length from the top, a diameter of wood whose third power is proportional to that length. Such a beam (of uniform resistance) takes on the shape of a paraboloid (Metzger C - cited in Busgen and Munch 1929). The broadleaf tree also has a trunk tapering from the base to the apex, but its structure may be further complicated by large branches growing from various points of the trunk. The broadleaf tree may not therefore conform so well to the model of simple fixed beam.

In likening the tree to a beam it is assumed that the tree will react to the incident forces in a manner similar to that known to occur in the simple beam. Young's Modulus of Elasticity (E) along the grain of the tree is therefore a measure of the resistance to deflection, or its effective rigidity. Large values of E indicate a more rigid material. Discrepancies and complications should be expected due to the presence of branching, rot and other inherent weaknesses in the trees. Conifers are fast growing and produce soft wood, whilst broadleaf trees generally consist of denser, harder wood. Air-dried timber has higher values than green (unseasoned) timber (Table 2.1). Living timber, which includes bark, is found to have smaller values of E than green timber (Vafai and Forshand 1979, Mamada et al 1984, Nakatani et al 1984 - cited by Cannell & Morgan 1987).

Branch wood has still lower E values (Cannell & Morgan 1987), though it must be noted that these tests were carried out on young timber (5 and 13 year old), rather than the mature trees used by other researchers. Cannell and Morgan (1987) found that E also showed great variation between species, and were able to conclude that branches of *Pinus contorta var. latifolia* (Lodgepole pine) were more flexible than *Larix decidua* (Larch), *Picea sitchensis* (Sitka spruce) and *Betula pendula* (Silver birch). Values of E calculated without bark were about 50%

greater. Much of the variation could be attributed to the specific gravity of the specimens or the percentage water content.

At any height in a stem of circular cross-section the resistive bending moment **B**, is given by:-

$$B = \frac{\pi h^4 E}{4 H} \qquad 2.1$$

(Brown , Panshin and Forsaith 1952 - cited by Petty & Worrell 1981)

where **E** is the mean modulus of elasticity, **H** is the radius of curvature of the base of the stem and **h** is the radius of the trunk at the given height.

Trunk breakage would occur if the incident force was greater than that which could be withstood by any part of the stem. At failure the bending moment reaches a maximum $\mathbf{B_{max}}$:-

$$M_{max} = \frac{P_c \pi h^3}{4} \qquad 2.2$$

where $\mathbf{P_c}$ is the breaking stress for green timber, (30 to 60 MPa for green soft woods - Sunley 1968).

A wide range of breakage heights were observed in catastrophic winds, which supports Petty and Worrell's argument (1981) that trees are designed to stress equally along the outer sheath of wood - that is they are as likely to break at any point. Leiser and Kemper (1973) investigated the stress distribution in trunks of sapling broadleaf trees - *Ceratanin siliqua* (Carob), *Gingko biloba* (Gingko), *Liquidamber styraciflua* (Sweet gum) and *Betula verrucosa* (European White Birch). This was done mathematically on a computer and subsequently verified with actual samples. A trunk taper parameter, **Q**, was calculated:-

$$Q = - \frac{(e - r)}{e} \qquad 2.3$$

where **e** is the radius of the trunk at the base and **r** is the radius of the trunk at the point of loading. Results showed that for a taper parameter of -0.6, stress was at its minimum and most uniformly distributed. It was seen that the maximum stress for an untapered trunk would occur at the base whilst in a tapered trunk, stress was relatively uniform for 2/3 of the length, before dropping rapidly to the tip. It is of additional interest that all species were seen to develop this -0.6 taper parameter, particularly as they were of varying stages of evolutionary development.

King (1981 and 1986) carried out work on *Populus tremula* and *Acer saccharum* (Sugar Maple) measuring heights, diameters, crown and trunk mass and tree form from saplings to mature specimens. Basing a stability safety factor on the actual trunk diameter and the minimum diameter required to support the tree, it was concluded that *Acer saccharum* had a higher stability factor than *Populus tremula*. King related this to the density of the wood and its place in the woodland succession. *Populus tremula*, a pioneer species, has a green wood density of 350 kgm^{-3} excluding water as compared to *Acer saccharum* (a climax species) with a density of 560 kgm^{-3}. High density wood may provide the best combination of flexibility and strength to withstand high winds, whilst low density wood is more efficient per unit dry mass for withstanding buckling (King 1986). This is because the trunk of the low density wood will be of greater diameter and hence more rigid than a higher density trunk of equal weight (equation 2.2).

Morgan and Cannell (1987) have also studied the tree as a cantilever beam which may undergo large deflections. They have developed a method of structural analysis which can cater for the beam being tapered and subject to complex loading. The analysis involves the beam being made up of a number of segments. Applying their equation, the stress conditions at any point on the trunk, can be calculated providing initial conditions at a point and the loading are known.

Age is a further factor to be considered. The trees' properties vary throughout the life of the tree. As the tree matures, the diameter : height ratio increases, and so the tree becomes apparently more stable. Also the stiffness of a cylinder is related to the fourth power of its diameter and so a tree of large diameter is likely to be more stable. However the tree's crown is likely to increase as the tree matures and the interception of more wind will tend to make the tree less stable. At the point when the crown nears its maximum size it may be hypothesised that if the trunk diameter were still increasing, then the tree would become more stable. However, if this does not occur until the tree has reached maturity and started senescence, the stability gained may not counteract other ageing processes. Rot and defects present in many older trees may make them more vulnerable to wind damage. The position of such weaknesses, either in the roots or the trunk will affect the likelihood of the tree uprooting or suffering trunk breakage.

2.2 Experimental observation of natural and artificial loading

2.2.1 Static Loading

In order to calculate the forces required to cause tree failure, artificial or static loading have been carried out using hand winches and pulley systems. During experiments by Fraser (1962a) it was noted that the loading should be steady and reasonably quick to prevent the tree from 'tiring', i.e. undergoing load relaxation. This process would increase the tree displacement if the tree were held under a particular load for any length of time. Fraser and Gardiner (1967) found maximum turning moments of 40 to 52 kNm with *Picea sitchensis* growing on brown earth and peaty gleys respectively. These values were similar to those of Fraser (1962a). Coutts (1986) attained turning moments for uprooting, of 10-50 kNm, for 20 m high *Picea sitchensis*, while Blackburn, Petty and Miller (1988) observed moments of 3-14 kNm for their 10 m high trees. All these values are similar if the turning moment/ stem weight relationship is considered.

Blackburn et al (1988) found that static turning moments were closely related to the cube of the diameter at breast height (dbh^3) and to the stem weight. Further experiments confirmed that stability was greatest in the sturdy suppressed trees (lower in height with increased trunk diameters) than in the taller slender trees. This conclusion was based on the trunk diameter/ height ratio, also investigated and confirmed by Sugden (1962) and Mayer (1989).

Blackburn (1985) also carried out an experiment in which trees were pulled to the point of soil breakage, then released. On re-pulling it was found that although initial deflection was greater with a given force, the value of the uprooting force was not lowered. This cannot really be described as dynamic loading, but it does suggest that tree anchorage may be loosened by excessive tree movement which may make the tree more susceptible to wind throw when the dynamic process of uprooting is considered.

During all the experiments described above, tree failure by trunk breakage was not reported. As trunk breakage has been seen to occur in storms in close proximity to uprooted trees (personal observation), it was concluded that either the loading of the trees in these experiments was such that uprooting was favoured, or that the results of trees which suffered trunk breakage were discarded. Assuming that such tree failure would be reported if it had occurred, then this suggests that the method of loading does not realistically simulate wind loading. This suggests that the dynamic movement of trees in the wind is a factor in the promotion of trunk breakage.

2.2.2 Wind Tunnel experiments

Wind tunnels have been used to determine the relationship between the wind velocity and the forces acting on trees. Forces exerted in the direction of the flow are conventionally called 'drag'. The drag coefficient is a ratio which expresses the actual force exerted on an object in relation to the maximum force which would occur if all the air flow were intercepted.

For a solid building, the drag (**D**) is directly proportional to the square of the wind velocity (**V**):-

$$D = C_D \frac{1}{2} \rho A V^2 \qquad 2.4$$

where ρ is the air density, **A** is the building area presented to the wind, and $\mathbf{C_D}$ is the drag coefficient.

The ability of trees to streamline reduces the cross-sectional area (**A**) of the tree and correspondingly the wind interception. Thus the drag for trees becomes more nearly linearly proportional to the mean velocity (**V**). Alternatively it can be said that the drag coefficient decreases as wind velocity increases.

Specimens of *Pseudotsuga menziesii* (Douglas Fir), *Pinus sylvestris* (Scots Pine), *Picea abies* (Norway Spruce) and *Tsuga heterophylla* (Western Hemlock) 8.2 m high, were subjected to winds of between 9.8 and 29.3 ms^{-1} in the wind tunnel with measured drag forces varied from 0.2 - 2 kN (Fraser 1962b). Weights of the stem and branches were also measured and found to be closely related to the rate of increase of drag with increasing wind velocity. Indeed it was found that tree weight appeared to account for more variation than did tree species. Tree weight however does not appear in the drag equation (2.4), but since mass is likely to be approximately related to the area, A, an increase in mass would lead to an increase in area and hence an increased drag.

Mayhead (1973a) verified Fraser's results using a wind speed of 30.5 ms^{-1}, a wind speed likely to cause wind throw, to derive drag coefficients of eight coniferous species. At this wind speed the drag coefficients were found to vary from *Tsuga heterophylla* 0.14, *Pinus sylvestris* 0.29, to *Abies grandis* (Grand Fir)

0.36. This variation was attributed to the rigidity and density of the foliage of *Abies grandis*. *Tsuga heterophylla* at the other extreme is very supple with short needles and fine branches. Branch weights were not measured in this experiment.

A knowledge of drag at specific wind velocities can enable overturning moments (the actual force required to uproot a tree), to be calculated, and vice versa, turning moments gained from static uprooting experiments enable drag forces to be calculated, and hence the wind velocities required for uprooting determined. The following equation shows the above calculation method, with specific assumptions:-

$$U = F \cdot g \qquad 2.5$$

where **U** is the turning/ uprooting moment, **F** is the applied force, and **g** is the distance of that force from the fulcrum. Fraser (1962b), assumed the force to be a point source acting on the centre of the trees' crown, that is with **g** at approximately two thirds the height of the tree. The force **F**, incident on the tree is the drag of the tree (equation 2.4). As drag is known to vary with wind speed, experimental results are required to relate the drag force to wind speed, (which will vary for different tree species), and hence the wind speed likely to cause uprooting can be estimated.

Fraser (1962a) measured the overturning moments of three *Pseudotsuga menziesii* to be 50 kNm, 54 kNm and 78 kNm. The first two trees were pulled over before a gale with wind speeds of 25.7 ms^{-1}, and the third tree afterwards. The drag for each of the three trees was calculated for this wind speed (assuming them to be still standing), and also an estimate of the turning moment of each tree. This estimated moment was greater than the actual turning moment for the first two trees, but much less for the third tree. This would predict that the first two trees would have been uprooted in the winds, but the third would not. Although these results cannot be confirmed for the two trees uprooted before the strong winds, the third tree withstood them as predicted.

Recent storms in Britain, which had devastating effects on trees, had wind speeds gusting to 42 ms^{-1} (Task Force Trees 1988). Serious and widespread damage can occur even at a wind speeds of 30.5 ms^{-1} (Mayhead 1973a). Endemic wind throw occurs in conifer plantations in Scotland in normal winter gales in which winds gust between 16.5 ms^{-1} and 30.4 ms^{-1} (Cannell and Coutts 1988). Actual observations of wind throw and corresponding wind measurements therefore suggest that loads calculated by static analysis over-estimate the critical wind speed (Oliver & Mayhead 1974, Blackburn 1985).

To the author's knowledge the only wind tunnel drag tests which have been carried using broadleaf trees involved only the testing of single leaves or small clusters. The leaves were found to have decreasing drag coefficients with wind speeds increasing from 10 ms^{-1} to 20 ms^{-1}, Vogel (1989). Drag coefficient values varied from 0.6 for *Liriodendron tulipifera L.* (Tulip tree) and *Carya glabra* sweet (Pignut hickory) to greater than 3 for *Quercus alba L.* (White oak). These values are much greater than those calculated for conifers (Mayhead 1973a). It was noted however that the clusters of leaves had lower drag coefficient values than the single leaf, and this may be expected to reduce further if the cluster size was increased, ultimately to an entire tree crown. The drag coefficient of broadleaf trees like conifers is likely to be vary on the density of foliage and the streamlining response of the tree. Leaf shape, arrangement and flexibility vary between species as does branch structure and stem elasticity.

2.2.3 Dynamic Loading

Wind cannot be considered as a static force and so the progressive winching of trees, though informative, did not realistically simulate wind loading. Further investigation was required to increase the knowledge of tree stability. This included observation of both the wind and the tree.

The turbulent gusting flow of the wind is caused by obstacles in its path and by the roughness of the ground. Wind may be defined by a mean wind speed, but the amplitude and frequency of gusts are also important. In order to monitor the dynamic loading of the wind and the dynamic response of the tree, full scale testing in windy conditions is required. The length, frequency and energy of the wind gusts must be monitored simultaneously with tree motion so correlations can be made. A gusting wind cannot realistically be simulated in wind tunnels at large scales, nor can scaled down models of trees be produced which accurately represent the tree in every parameter (for example, drag, bending characteristics, deflection), though an attempt has been made to model the characteristics of a coniferous forest (Gardiner 1989).

Wind turbulence causes the tree to sway. Trees have natural sway periods and respond most to wind gusts of that frequency (Milne 1988). Resonance occurs at which energy is transferred to the tree causing sways of large amplitude. When the wind gusts do not induce natural frequency sway, much higher wind speeds would be required to induce the same damage .

Perfect resonance has not been observed by monitoring in the wind, however large oscillations have been set up by gusting and dynamic load factors of 0.5 - 5 over the static load values were recorded (Blackburn et al 1988). Increasing the dynamic load factor from 1 (equivalent to static load) to 2, reduced the critical (or uprooting) wind speed by approximately 40%.

The method for establishing the sway period used by Sugden (1962) was to physically push and pull the tree rhythmically at breast height until resonant motion was observed. Five successive vibrations were timed and the sway period calculated - values of 1.5 to 5 seconds were obtained for *Pinus resinosa* (Red pine) and *Pinus strobus L.* (White pine). Holbo et al (1980) found sway periods of 4-5 seconds for *Pseudotsuga menziesii* using displacement transducers in conjunction with anemometers and Gardiner (1989) found sway periods of 2-4 seconds for *Picea sitchensis*.

It was noted that the trees Holbo et al (1980) observed were 26-30 m in height, with sway periods of 4-5 seconds whilst Milne (1988, 1990) and Gardiner (1989) reported conifers 13 - 15 m high, to have sway periods of 2-4 seconds. This suggests that the tree sway period may possibly be affected by height. Sugden (1962) attributed the sway period, to the mass and distribution of the crown, and found trees which were stockier, that is, those with a higher trunk diameter to height ratio, vibrated with a shorter time period.

Mayhead (1973b) also studied the sway periods of forest trees, with particular attention to the parameters which may be those influencing the sway period. He concluded that the best analogue to describe the tree (76.4% of variation accounted for), was that of a uniform metal rod of length **w**, firmly fixed at one end, of mass **M**, and diameter, **y**. When vibrating at its natural frequency it will have a sway period, **W**, given by the following equation:-

$$W = \gamma \frac{w\sqrt{Mw}}{y^2} \qquad 2.6$$

where γ is a dimensional constant which varies according to the shape and mass distribution of the uniform metal rod. It should be noted that the mass, length and diameter (at breast height) are all inter-related.

Trunk stiffness also determines the sway amplitude of the tree. This is dependent on the trunk's inherent elasticity (Young's Modulus) and the diameter of the stem (Section 2.1).

Milne (1988) produced an equation to relate the movement of the tree to the incident force arising from the gusting winds. This effective or drag force, **F(t)**, of the wind was calculated to be equal to an inertia force (related to the mass of the crown), a bending force (related to the springiness of the trunk) and a damping force.

$$F(t) = \frac{M_c d^2x(t)}{dt^2} + c\frac{dx(t)}{dt} + kx(t) \qquad 2.7$$

where $\mathbf{M_c}$ is the mass of the crown, **k** is the spring constant of the stem, and **c** is the damping coefficient. Damping acts to reduce tree movement and is a feature of the tree itself, branch movement, the rooting system and contact with neighbouring trees.

Most of the above work was carried out on plantation conifers, especially *Picea sitchensis*. Wind behaviour within and above the canopy differs from the case of the isolated tree and there is also canopy interaction causing damping. Tree growth within a plantation is very different too, and the varying tree parameters will consequently have a major effect on tree movement. Within the plantation, tree height alone appeared to be the major parameter to consider due primarily to the increased wind interception, and also to the centre of this wind pressure being farther from the base of the tree, therefore increasing the turning effect. On this principal the forested parts of the country have been classified into areas according to their susceptibility to wind throw. This, 'The Wind throw Hazard Classification', is based on a critical height, which is the average height of the 100 trees of largest diameter in the stand, at the onset of wind blow (Miller 1985b). This critical height is not determined by the species alone but more so by the location. Trees of the same species, that is, *Pinus contorta var. L*, *Picea sitchensis.* and *Pseudotsuga menziesii*, growing in North America may grow to 50 m, as opposed to the 15 to 25 m they may achieve in Britain.

Miller (1984, 1985a) also studied the effect of thinning and wind interaction, using wind profile analysis and eddy correlation techniques. He measured zero plane displacement, roughness length, frictional velocity and profile shear stress. Results suggested that turbulent wind fluctuations within a frequency range 0.01 to 1.0 Hz are likely to couple effectively with individual trees and exchange momentum. The spectral energy of the wind within this range was found to increase by 27% after first thinning and after the second thinning was 41% higher than the unthinned stand. Increasing the initial spacing of trees, reduces light competition, and the trees grow with a greater trunk diameter as a result of being exposed to higher wind levels since planting. Experiments have shown that the critical wind speed does increase with increased spacing (Blackburn et al 1988). It was also noted that tree stability decreases for an increase in height from 7 to 11 m and then increases at heights of 11 to 18 m. This suggests that the growing pattern of the tree trunk diameter and height do not increase uniformly.

2.3 Adaptation and selection

The literature review has highlighted various parameters of trees and their behaviour in static and dynamic conditions. It must be noted however that there is variation from tree to tree, between species, and also between conifers and broadleaf trees. This being said however, it must also be recognised that trees as living organisms have the ability to adapt to different environments and conditions. Methods of adaptation may be different for different species - there is not one right way. Biological selection processes will determine which adaptations are most successful and be quantified by the number of each particular species in any given environment.

It is generally accepted that trees can respond to wind and can alter their dimensions accordingly. However stability is only brought to an adequate level, as the tree requires energy for other survival mechanisms - flowering, leaf growth etc. The tree may not therefore be designed to withstand the very extreme conditions which occur only very infrequently.

Tree height and structure may develop differently for example. Trees in more exposed sites tend to be stunted - that is have a thicker trunk and grow to a lesser height. Biological investigation of these trees will reveal the growth of 'reaction' wood. In conifers, compression wood forms on the underside of branches and leeward side of the trunk (Cannell and Coutts 1988). The fibres in the wood have thicker walls and are denser than those in normal wood. The wood is strengthened to withstand compressive forces - containing more lignum and less cellulose than normal. In broadleaf trees, tension wood forms on the upper side of branches and windward side of the trunk. This wood is developed with fewer vessels relative to fibres, to increase the tensile strength. The fibres have thicker gelatinous walls and less lignum than normal. This reaction wood however lowers the value of timber, as it makes the wood more prone to warping. Because of this reaction wood, estimates of site average wind speed and direction can be made (Wade and Hewson 1979). Robertson (1987), showed this as ratio of the unevenness of the trunk providing the terrain is not too steep :-

distance of pith to bark on leeward side	:	distance of pith to bark on windward side

Another means of adapting is to grow non-vertically with the prevailing wind. A deformation index has been used to calculate wind speed by measuring the stem deflection from the vertical.

Woodland trees of both conifer and broadleaf types have slightly different dimensions and properties to their isolated counterparts. Trees growing in woodland or in close vicinity to other trees compete for light. This promotes increased height growth at the expense of radial trunk growth. Structurally these trees still maintain an adequate level of stability owing to the fact that wind levels within the plantation are greatly reduced by sheltering from neighbouring trees. Thinning operations can cause problems and initiate wind throw, as the environment which the trees have adapted to is altered dramatically and almost instantaneously.

2.4 Roots and Soil

Tree roots complete the system and really ought not be considered as a separate issue. They are a major factor in tree stability, but they cannot be considered without bearing in mind all the factors discussed above. The position of the centre of gravity, for example, is also very important, as once it is displaced beyond the turning fulcrum, the weight of the tree will help to pull the tree over. Uprooted trees and trees with stem breakage are often found in close vicinity following strong winds, indicating, perhaps, that trees develop similar levels of resistance to wind loading in both stem and trunk systems.

Information on roots and root growth is sparse due to difficulties in observation. Atkinson (1980) describes methods of excavation, observation, sampling, root activity and other indirect methods of monitoring the roots. Coutts and Lewis (1983) and Reynolds (1983) alternatively studied the development of roots by analysis of growth rings. Estimating the root quantity in the soil from aerial observations proved unsuccessful as the root-shoot ratio of trees was found to be affected by light, soil, age and wind (Helliwell 1989), but not by competition or tree spacing (Fraser 1964).

2.4.1 Root system development and structure

Root growth is initiated by the growth of the radical - the first root which is a strongly geotropic tap root (Wilson 1970 - cited by Patch 1983). This root was once thought to be the stabilising part of the tree. However, this line of thought was dismissed by findings typical of that by Weaver and Kramer (1932). The roots of a 65 year old specimen of *Quercus macrocarpa* (Burr oak), 11.4 m tall with a basal diameter of 336 mm were carefully studied. The tap root tapered rapidly to 114 mm at a depth of 1.0 m, 94 mm at 1.5 m, 44 mm at 1.8 m and was traced to a depth of only 4.3 m. Some thirty major lateral roots had developed, most in the top 0.6 m of soil, with a spread of 6 - 18 m. Ruark, Mader and Tattar (1982) found 60% - 80% of the root volume, especially the fine roots, within the top 20 cm of mineral soil. Hintikka (1972) describes *Picea* (Spruce) as lacking a tap root and the root mass moving like a plate, rocking in the wind.

The bulk of the broadleaf tree's roots are generally found under the crown, with those of open growing trees extending somewhat further (Helliwell 1986). Kramer and Kozlowski (1960), however, found roots 2-3 times beyond the crown radius in open grown trees, although the majority of active roots were below the periphery of the canopy.

Roots also develop to suit the physical conditions of the soil and the size and shape of the grains and aggregates. Roots developed in fine textured soil are shorter and more branched. In poorer, lighter, well-aerated soils, roots tend to be larger, thinner and straighter (Ruark, Mader and Tattar 1982).

Neustein (1964) reported a broad correlation between rooting depth, tree height and incidence of wind throw. Soil type is a major factor in root development and in tree stability, particularly where rooting depth is concerned. The soil characteristics, particularly those concerning the water regime, infiltration and drainage rates, will control the level of the water table. Rooting depth may thus be controlled as continual/ frequent water-logging will kill the roots especially, in the growing season.

Rooting depth is also influenced by the site and proximity to other trees. The isolated tree will tend to have a shallow, wide spreading root system, whereas that grown in a plantation will show increased depth - becoming deeper the closer the spacing of the trees (Henman 1964). This may be due to increased competition for water and nutrients at near-surface level, or because the increased water demand has reduced the water table. Another factor is that the plantation trees, particularly conifers, are grown on ploughed ridges. Roots rarely cross the furrow, and so root growth tends to be downwards. Pyatt and Booth (1973) compared planting of ploughed land with hand-prepared turf. The greater rooting depth and greater root weight attained on the ploughed land, which was consequently drier, did not compensate for the reduced moment capacity resulting from the reduced root spread restricted by the furrows, and hence these trees were not as stable. It was found that the trees in wider spaced stands are more stable than those grown closer together (Blackburn, 1985). This may be partly to the greater radius of the root spread, which effectively moves the uprooting fulcrum further from the base of the tree, making overturning more difficult, and partly due to the increased stem diameter. It was also noted that for the wider spaced stands, wind damage by stem breakage increased in relation to the uprooting of trees.

Like the aerial parts of the tree, root formation and development is very species dependent as well as being influenced by the external environment. Root structure is developed throughout the life of the tree and changes with age and changing environmental conditions.

2.4.2 Tree Roots and Soil as Components of Tree Stability

Uprooting is a process which involves a variety of mechanisms. Roots on the windward side are in tension, whilst those on the leeward side are subjected to compressive and bending forces. The soil/ root interface will also be experiencing forces, which may be compressive, tensile and/ or shear depending on the location.

2.4.2.1 Windward Side Forces

Roots on the windward side are subjected to tension forces rather than compression. The roots will either be snapped or will shear through the soil, unless they are lifted within the soil/ root-plate. For maximum strength, all the roots should be evenly loaded.

Soil shear strengths of 1.3 $\times 10^{-2}$ MPa have been determined for the soil beneath *Picea sitchensis* stumps on peaty gley (Smith 1985). Soil shear strengths are much less, more than 3 orders of magnitude less, than the roots under tension which have tensile strength values of 15 to 63 MPa (Coutts 1983). The importance of the soil strength may therefore be thought to be minimal, however this is not the case. The strength of the soil/ root interface will determine the size of the soil/ root-plate because, at the soil/ root interface there will be friction. This will be increased with increasing root tortuosity. This fact may be an intrinsic characteristic of the tree species, or a result of soil conditions and size of the soil particles. To the point at which the root's tensile strength is greater than the friction, then the root will be pulled through the soil. At a point, when the root diameter has reduced, the friction may be stronger than the root itself, and hence the root will break. Thus the soil/ root characteristics affect the size of the soil/ root-plate which thus affects the quantity of soil which therefore has to be moved if uprooting is to occur, and hence the uprooting forces required.

Soil strength varies with soil type and soil moisture content. Coutts (1983) found that in clay soils the roots did not break but pulled out. Anderson et al (1989) carried out root extraction force measurements for *Picea sitchensis* in brown earth and peat. Despite the brown earth being drier and containing deeper roots, the root diameter at the pulled end, the length of root extracted and the root displacement at maximum extraction force, were similar for both soils. Slightly more force was required to extract roots from peat as oppose to the brown earth. This difference is small however and is not significant in tree stability particularly as *Picea sitchensis* was found to be more firmly anchored on brown earth than on peaty gley (Fraser and Gardiner 1967).

The shear strength of soils decreases with increasing moisture content (TRRL 1979) and hence stability will decrease as soil is wetted.

Tree pulling experiments in North Wales (Fraser 1964) produced results from which soil types (recognised in the, then, current soil survey) could be given a wind damage susceptibility rating. Miller (1985b) classed soil into three broad groups according to rooting restrictions, for the purpose of wind throw hazard classification. This grouping doesn't relate tree stability to the actual soil type, that is clay, sand, or silt, but only to the depth to which the roots can penetrate before waterlogging. This may suggest that tree stability doesn't vary considerably between soil type, or that the difference is minor when compared with the stability of trees on peat soil, or the even more waterlogged peaty gleys. It must also be noted that the majority of forest plantations, for which the wind throw hazard classification was intended, are situated on the less favourable soils, generally at high altitudes and very exposed.

2.4.2.2 Leeward Side Forces

Roots follow the same principles of strength as the stem and crown. The diameter of the roots affects the flexibility. Wind induced bending moments can cause the development of uneven growth with the roots tending to become 'waisted', that is with an 'I' shape cross-section. Waisted *Picea sitchensis* roots have been found to be three times more resistant to bending than comparable roots of circular cross-section (Cannell & Coutts 1988). However the resistance of the tree's system to bending will not necessarily increase three fold. Bending takes place in the zone of weakness - at the point where the root tapers rapidly (Wilson 1975 - cited by Coutts 1986). The increase of bending stiffness due to the waisting causes the fulcrum of the soil/ root-plate to move away from the stem base and hence uprooting becomes more difficult (Deans and Ford 1983), although not normally by a factor of three.

The finer tree roots may contribute in drying the soil thereby altering it's suction forces, but they are of little significance when considering the bending forces on the leeward side of the tree. Branching of roots is similarly very important - a root system containing only a few thick lateral roots at the stem base will be stiffer than one containing many thin roots. This is especially important on the leeward side of the tree as the main laterals here act as the fulcrum about which the tree will overturn. However few thick laterals create wide angles between them which effectively shortens the lever arm (**u**) on the leeward side.

$$u = f\cos(\frac{\beta}{2}) \qquad 2.8$$

Where **f** is the root length proximal to the fulcrum where the roots bend and β is the angles between roots. **u** is found to be very sensitive to angles greater than 60°, that is when fewer than six laterals are spaced evenly around the tree (Coutts 1983).

Coutts (1983 and 1986), studied the components of stability of *Picea sitchensis,* a conifer, on peaty gley soil. Whilst forces were being applied to the trees, Coutts (1986) measured vertical soil and root movements using linear potentiometers, similar to the method used by Hintikka (1972). The soil/ root-plate was observed to rise to 60 mm on the windward side and was depressed by 15 mm on the leeward side. Soil and root breakage were monitored by using a tape recorder with microphones buried in the soil. The formation of a soil failure crack was recorded below the stem base on the windward side of the tree and its extension in both leeward and windward direction was traced. Crown and stem positions were monitored simultaneously to evaluate the weight distribution. The results are summarised in Figure 2.1.

The same principles of stability are thought to apply to broadleaf trees too, though the values and relative importance of each component may be different. Varying depth of roots, root-plate diameter, and soil type are likely to affect these values too.

2.5 Points arising from the literature review

The literature review has produced valuable information about the behaviour of a number of coniferous species in windy conditions. However it has also revealed a relative lack of corresponding information on broadleaf trees, particularly those native to Britain.

The literature review has confirmed that tree stability is a complex issue, with the issue further complicated by biological variability. All parts of the tree, both above and below the ground are involved. In addition the immediate environment, that is the soil and ground condition, is important. Likewise the aerial environment, in terms of the wind characteristics has its effect on the tree.

Detailed information on the structural root system of the tree, root depth, type and spread was particularly conspicuous by its absence. Indeed a comprehensive database of all the tree's parameters, especially those of fallen trees, would enable tree response to high winds to be further investigated.

The spread and depth of the major roots, before they branch too diffusely, is thought likely to affect the trees stability. It would be difficult to predict when a root is too small in diameter to be categorised as a structurally important root. The best method is probably to observe the root-plates of uprooted trees and measure the root-plate radii and the root diameters at the point of breakage, or the distance the roots had been pulled through the soil without breaking. This specific type of information was not available at the onset of this research at Nottingham University.

The literature highlighted the limited applicability of static measurements to tree fall in high winds. The difficulties in physically modelling individual trees for scaled down wind tunnel observation also became apparent. With the ultimate aim being related to the entire tree and its response in the wind, the merits of studying leaf displacement, or even twigs or branches, in the wind tunnel, appeared minimal. It appeared that the best approach is to monitor trees in the wind, although this too is not without shortcomings, particularly concerning the lack of control in the experiment. Static and induced dynamic measurements would also be required to support observations.

It was therefore decided that the course of this research should encompass a number of the topics on which information was found to be lacking by the literature review. Firstly, data collection, particularly of fallen trees, would be undertaken and the results analysed to increase the general knowledge and awareness of the problem of tree fall and root structure. It was hoped that this study would indicate specific areas required for experimental research. Then it was envisaged that the research would involve measurements of both static and dynamic tree movement.

Tables : Chapter 2

Mean Young's Modulus (E) GPa					
Soft wood (coniferous trees)			Hard wood (Broadleaf trees)		
Green	Air dried	Living	Green	Air dried	Living
7.6 [1]	9.6 [1]	2.4 [2]	8.9 [1]	11.4 [1]	7.5 [2]

1 - Hearmon 1984, Kollman and Cote 1968, Sunley 1968, USDA 1974, Bodig and Jayne 1982 - cited by Cannell & Morgan 1987

2 - Cannell and Morgan (1987)

Table 2.1 Young's Modulus (E) for air-dried, unseasoned and living timber

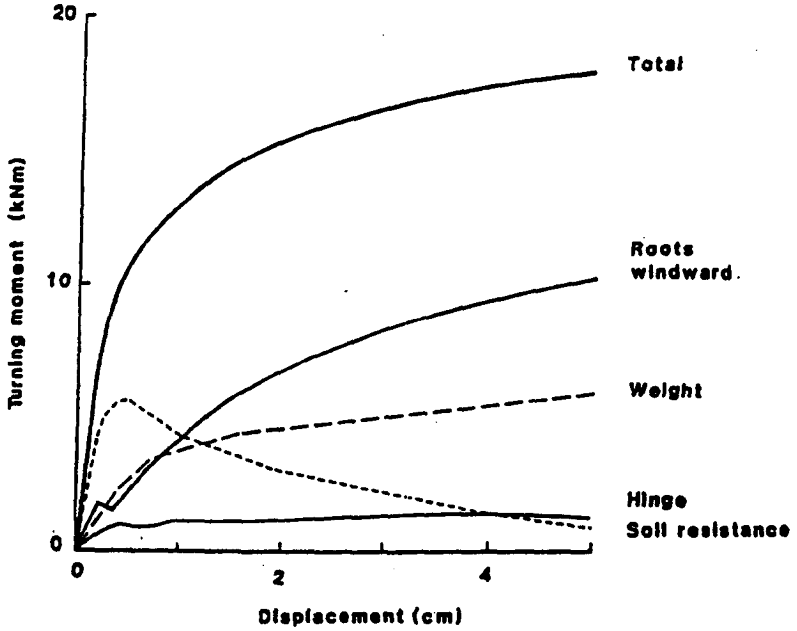


Figure 2.1 The Components of Tree Stability (Coutts 1986)

Chapter 3

Surveys of the 1987 storm-damaged trees

3.0 Introduction

The lack of information concerning tree fall or even tree population (excluding forest plantations) became evident during the literature review. Attempts to obtain records of fallen urban and roadside trees from County and local Borough councils, landowners, and insurance brokers proved futile. The emphasis was always on removing the offending specimen or specimens quickly to minimise obstruction and further danger. Paperwork was minimal with even the tree species rarely recorded.

Three independent data collections however were located, each containing large amounts of data. Two surveys resulted from the storm of 1987, which though very destructive, did provide a great opportunity of data collection. The third information source was a database established for tree maintenance purposes. Details of the three data collections are listed below.

i) 'The Wind Blown Tree Survey', a survey commissioned by Task Force Trees (Countryside Commission), and controlled and collated at the Jodrell Laboratory, the Royal Botanic Gardens at Kew ;

ii) 'A Survey of Park land Trees', a survey conducted by the Research Division of the Forestry Commission.

iii) A database of the trees growing on Council owned property in Essex.

Here the author would like to extend her gratitude to the three bodies who very kindly allowed unlimited access to their data records.

In this chapter, these surveys and their results are investigated and comparisons made of the genus composition and the trees' physical parameters with the ultimate aim being to improve knowledge of the incidence of tree fall and damage in high winds. During the 3 year period of research and experimentation associated with this project, the F.C. and Kew have both produced and published results from their own data (Gibbs and Grieg 1990, Cutler et al 1989, Cutler et al 1990, Gasson and Cutler 1990). In the comparison of the results it was hoped to expand on, confirm or contradict their findings.

Analysis carried out within this project has a particular bias towards the more common broadleaf species found in the surveys. Comparisons are also drawn with the conifers which are present in the data in the largest numbers. For the purpose of analysis tree species are grouped into genera. It is assumed that the species within a genus share similar characteristics, or at least that any genus is dominated by one or perhaps two major species, which have an overriding influence on the characteristics of that genus.

Specific details of each database are given (Section 3.1), followed by details of the actual data and any transformation it requires before it could undergo analysis (Section 3.2.1). Limitations of the data are also noted in that section. This is followed by a description of the analytical procedures used to compare the data sets (Section 3.2.2). Results are then be presented (Section 3.3) in an order corresponding to the description of Section 3.2.2, with the results of the first stage being used for the subsequent procedures. A discussion (Section 3.4) follows the results, in which selected results and their implications are examined in a broader environment. This includes examining differences in the genus composition of the data sets, and exploring possible reasons for them. Later in the discussion, the heights of the selected tree genera are compared to data by Mitchell and Wilkinson (1989) and relevant comments made. Points of interest about the aerial and subterranean tree parameters raised during the results are also discussed. Finally in Section 3.5 conclusions are drawn in which findings from the surveys are clearly stated.

3.1 Surveys and Databases

3.1.1 The Windblown Tree Survey (to be referred to as the 'Kew' survey).

Full details of this survey are presented in Cutler, Gasson, and Farmer (1989), but various points will be highlighted below. Only the data collected on the Form 'A', that is the single urban tree was used in this thesis. The survey has data on 887 trees collected throughout SE England. The survey sheets were completed by professional and interested persons in this area. The majority of completed forms report on uprooted trees, with only a small number recording just major crown damage or stem breakage. No reference is made to undamaged trees. Later analysis concerns only those trees that have been uprooted, as the number of crown/ stem damaged trees is too small to support statistical analysis.

3.1.2 The Survey of Park lands (to be referred to as the 'F.C.' survey).

In this survey 20 park land sites in SE England were selected. Gibbs and Greig (1990) gives full details. The survey was conducted by a small number of F.C. employees whom first collected data on 1023 storm damaged trees, then later recorded details of some 2878 undamaged trees that closely neighboured the damaged specimens. (Numbers vary slightly from those published by the F.C. due to data editing). Analysis of this data is based on three data sets; undamaged trees (2878), uprooted trees (447), and trees that were storm damaged but remained standing (576). This latter group will be referred to as 'crown damaged' trees.

3.1.3 The Essex Database.

Essex County Council were in the process of collating a tree database for routine maintenance purposes when the 1987 storm struck. The data comes in three separate sections; street trees, school trees and trees on other council sites; libraries and fire stations for example. These categories were simply a structure in which to collect the information. The database was compiled over a period of three years, by three different teams of forestry trainees.

The street tree data was entirely collected before the storm, and the 'other site' data entirely after the storm. The school trees were being surveyed when the storm struck. The Essex database therefore contains trees which were both damaged and undamaged by the 1987 storm. Trees which were uprooted on 'other sites' and some school sites would probably have been cleared before they were surveyed. The updating of the earlier database may have removed some information on fallen trees from the remainder of school sites and the streets which were surveyed before the storm occurred.

The storm followed a haphazard and scattered path through the SE England (Grayson 1988). This resulted in many areas of Essex suffering little damage, whilst other areas were damaged severely. The resulting tree population recorded in this database, (34684) though affected by the storm was still considered a valuable source of information and used to indicate the make up of the tree population. This was very important as it provided a very large database for comparing the two storm damage surveys with, particularly useful when species composition was investigated. The loss of information of some of the fallen trees however must be born in mind when conclusions are made. The major limitation of this database is that because it contains only standing trees, there is no information on tree root systems.

3.2 The Analysis

3.2.1 The Data

The surveys and database provided a large quantity of data for analysis. The independent sets of data had been recorded in different forms by each source and the actual information collected by the independent bodies also varied in its content. All the databases contained basic descriptions of the trees and their immediate environment. The F.C. survey also included specific details of tree diseases, whilst the Kew survey had more detailed information of the trees' physical situation. The Essex database included a five year maintenance programme. Not all the data was therefore required for the analysis. The data sets then had to be prepared into forms were the required variables could easily be read. Particular variables were selected as being important in numerically describing the trees. These were then used to compare the trees in the three data sets and also between selected subsets within each data set. These variables were height, crown spread, trunk diameter at breast height (dbh), root-plate spread and root depth.

It was not always possible to directly compare values of particular parameters between data sets. The heights for example have been recorded in metres by the F.C. and Kew, but in the Essex database they have been grouped into small, medium, large, and extra large (groupings of 5 m bands).

Special attention had to be given to ensure that parameters in each survey were recorded in the same units. The root depth presented by the F.C. for example, had been multiplied by 10 for ease of recording on their data sheet. Units also varied between the parameters, height was measured in metres, and trunk diameter in centimetres.

Missing values were expected in the data due to the difficulty in collecting the data. A fallen tree for example, may have had its crown removed because of the obstruction and inconvenience it caused, before the survey team reached it. Root data was absent where the tree remained standing. Occasionally the tree species was unidentified particularly if only the tree stump was being surveyed. In other instances data entry errors may have resulted in the removal of the value from the input data. These data errors could only be detected if values were very incorrect and physically impossible, for example a young *Fagus* (Beech) of 8 m high with a trunk diameter of 30 cm having a crown spread of 50 m. In such a case the 50 m would be substituted with a blank, still enabling the rest of the data to be used in analysis. In more questionable data sets the whole tree may have been removed from further analysis. As these errors could only be exposed during analysis slight numerical discrepancies may occur later in the results.

Genstat 4.04, (later Genstat 5) was the computer package selected for the analysis. It was capable of handling large data sets and also able to read the data in different but fixed formats. Missing values in the data sets were noted by the Genstat programmes, but did not disrupt the running of the programme. The package was capable of reading a number of variables simultaneously, and performing statistical analysis on them. It also allowed the restriction of data to one or more specific tree genera or species.

The package could be used for a great many statistical procedures, including the production of histograms and graphs. Regression lines could also be calculated and plotted. Numerical summaries produced during the analytical procedures helped in the detection of data errors.

3.2.2 Programme of Analysis

i) The initial step was to investigate the genus composition of the three independent data sets. This are presented as a series of pie charts with the differences in the composition of the data sets described. The fates of these tree genera in the 1987 storm were then investigated by looking at the genus composition of selected subsets of data from the F.C. and Kew data sets. Comparisons were then drawn with the Essex database.

The most abundant tree genera were then selected and used in further statistical analysis.

ii) Tree height was the next criteria to be examined. This again looked at the three data sets as a whole, and then at the heights of the selected genera. These results are presented as a series of histograms. Comparisons were made to investigate whether trees of specific heights are victim of particular fates.

iii) Analysis of all the trees' aerial parameters, height, crown spread, trunk diameter was then carried out. This involved the interaction of two of these parameters at once.

Comparisons were made to investigate whether trees which had succumbed to differing fates, had differing tree structures. Differences in trees' aerial structure was then investigated between different genera and species. The smaller trees from the Essex data base were then compared in aerial structure with the larger genera in the F.C. data sets.

iv) The subterranean parameters, the root-plate spread, and root depth were also considered and the interaction of these two parameters was compared between selected genera. Root-plate spread was then correlated with trunk diameter, and the resulting relationship again compared between genera.

Analysis involved the production of graphs with lines of best fit superimposed on them. Regression equations were calculated, for which values of the mean (regression gradient), standard error, intercept and the degrees of freedom are presented in Appendix A. Values are also given for the percentage variance accounted for, which serves as an indicator of the goodness of fit or correlation, of the drawn regression line.

From these regression equations statistical t-tests were carried out. (Details of the t-test are given below - equations 3.1 and 3.2.) Due to the complexity of this analysis and the number of combinations involved selected results only are presented in the form of regression lines drawn on graphs. These were chosen from the comprehensive set of t-test results (Tables 3.1-3.35) to illustrate specific points in the results, either differences or similarities.

The t-test is a two sample t-test where the values for **T** and **d.f.** (degrees of freedom) are given by the following :-

$$T = \frac{(\bar{j}_1 - \bar{j}_2)}{\sqrt{\frac{G_1^2}{N_1} + \frac{G_2^2}{N_2}}} \qquad 3.1$$

$$d.f. = \frac{((G_1^2/N_1) + (G_2^2/N_2))^2}{\frac{(G_1^2/N_1)^2}{(N_1 - 1)} + \frac{(G_2^2/N_2)^2}{(N_2 - 1)}} \qquad 3.2$$

where $\bar{j}$ = mean, **G** = standard deviation, **N** = number of observations

Values gained may be evaluated with the 95% (0.05) confidence level in Studentised t-distribution tables. For a null hypothesis, that is, there is no difference between the compared data sets, the **T** value will be less than the tabulated value. If the **T** value is greater than this, then the null hypothesis must be rejected declaring a significant difference between the data sets. Output from

Genstat programs produced values of mean ($\bar{j}$) and standard error values (s.e.) The standard error values was based on the root mean square (G^2/N). In the Genstat summary of analysis a residual d.f. was also produced which corresponded to the N-1 value used in the above equation to compare data sets.

3.3 Results of analysis

3.3.1 Data set genus composition

The F.C. and Kew species composition are given in Figs. 3.1 and 3.2 respectively. Eleven deciduous genera and two coniferous genera featured as important genera, with the remainder grouped into 'other broadleaf' and 'other conifer' as appropriate. The F.C. data had a relatively small number of tree within these 'other' groups (7%), whilst over 25% of the Kew data fell into these groups. Both the F.C. and Kew data sets had large numbers of *Quercus* (20%, 21%), and *Fagus* (11%, 15%). The F.C. data also had *Tilia* (Lime) (23%), *Aesculus* (Horse Chestnut) (12%) and *Acer* (Maple) (9%) as major groups with only a small proportion of the population taken by the other eight individual categories. Indeed approximately three quarters of the F.C. data was accounted for by five genera. The Kew data showed a much more even distribution of tree numbers between the genera, with *Acer* (4%), *Betula* (5%), *Carpinus* (Hornbeam) (3%), *Castanea* (Sweet Chestnut) (4%), *Fraxinus* (Ash) (4%), *Pinus* (Pine) (6%) and *Tilia* (6%) all with approximately the same proportion of trees. The remaining genera, *Platanus* (Plane), *Populus*, and *Cedrus* (Cedar) were deemed numerous enough in either or both the F.C. or Kew data to be considered as individual groups.

The Essex data when categorised into the same genus selection showed a greater proportion of *Acer* (13%) than either the F.C. or Kew surveys, with *Quercus* (8%), *Betula* (6%), *Fraxinus* (6%) and *Tilia* (5%) with the next largest percentages (Fig. 3.3). It was very striking that almost half (49%) of the database was comprised of 'other' genera, a substantially greater value than in either the F.C. or Kew data sets. When the Essex data was split into subsets (Fig. 3.4), school, street, and other site trees, this trend was found to be particularly pronounced in the street tree population (61% other genera). Investigation of the 'other ' category in the Essex data sets (Fig. 3.5) revealed very large numbers of *Malus* (Apple) (12%), *Prunus* (Cherry or Plum) (24%) and *Crataegus* (Hawthorn) (14%) in particular, with quite a large number of *Sorbus* (Whitebeam) (12%) also present in the school sites.

To consider the fate of the tree genera, the F.C. data was split into three subsets showing the tree genera proportions to alter slightly (Fig. 3.6). The F.C. data showed 74% of the total tree population to be undamaged, 11% to be uprooted, and 15% to suffer crown damage. The undamaged trees still showed the major groups, *Tilia* (23%), *Quercus* (18%), *Fagus* (11%), *Aesculus* (11%) and *Acer* (10%) to be present in high numbers. Indeed it should be noted that the undamaged subset was the major subset of the total tree population and therefore dominated the results. The fallen tree population comprised of a great number of *Tilia* (35%). *Fagus* (15%) and *Quercus* (14%) were also fairly prominent and present in the same proportion as in the undamaged tree population. *Acer* (4%) and *Aesculus* (4%) were minor groups however and were much smaller than in the undamaged population.

The crown damaged tree population consisted of a very large proportion of *Quercus* (32%) and an increased proportion of *Aesculus* (20%) compared with both the fallen and undamaged trees. *Tilia* (11%) and *Fagus* (9%) were the next largest groups, but their numbers were greatly reduced than in either of the other subsets.

The Kew data (Fig. 3.7) showed *Fagus* (15%) and *Quercus* (21%) to be the most commonly encountered genera in it s the fallen tree population. These were also prominent in the F.C. data. However *Tilia* (6%), which dominated the F.C. fallen data, did not appear as significant in the Kew data showing only similar proportions the *Acer* (4%), *Betula* (5%), *Fraxinus* (4%) and *Pinus* (6%).

The fate of each tree genus was further highlighted in histogram form (Fig. 3.8a) with the F.C. data being plotted to show the proportion of each genus which succumbs to each fate. This clearly displayed that *Acers* suffer little damage, *Tilia* and *Fagus* were most prone to uprooting and *Aesculus* and *Quercus* were particularly susceptible to crown damage.

The fates of some of the minor genus were also considered (Fig. 3.8b). *Betula* was seen to be very susceptible to damage. *Carpinus* and *Fraxinus* were seen only to suffer crown breakage, with *Fraxinus* being the more frequently damaged. Indeed *Fraxinus* was observed to incur proportionally the same amount of damage as *Fagus*. It was observed that *Castanea* suffered damage to only 25% of its' population, with the type of failure equally distributed between uprooting and crown breakage. In contrast, almost 70% of the *Populus* population was damaged with a significant bias towards crown breakage. *Platanus* was slightly more prone to uprooting, but less than 20% of the population was damaged at all.

Trees grouped into the 'other broadleafs' category showed a great vulnerability in the high winds, with approximately 85% suffering damage of which the greater majority was uprooting.

Pinus, *Cedrus* and indeed the 'other conifers' were less frequently observed to suffer damage. Less than 30% of the population showed any form of damage. Uprooting was slightly the more frequent form of damage, except for *Cedrus* which showed a small bias towards crown breakage.

The most commonly occurring genera were selected for further analysis, ***Acer***, ***Aesculus***, ***Fagus***, ***Quercus*** and ***Tilia***. ***Pinus*** and ***Cedrus*** were the selected conifers. ***Prunus***, ***Malus*** and ***Sorbus*** were also considered, though with reference only to the Essex database.

3.3.2 Tree heights

An obvious factor to investigate related to wind damage was the tree height, to see if it was perhaps the tallest trees which suffer most damage. Maximum values of approximately 40 m were recorded in the F.C. survey, with mean values of just greater than 20 m. The Essex database showed a smaller mean height. Histograms of tree heights for the various data sets and selected subsets have been produced (Figs. 3.9, 3.10, 3.11), to examine this parameter more closely.

In all the F.C. subsets and the Kew data it was seen consistently that the *Aesculus* population is smaller than the *Quercus*, *Tilia*, *Acer* or *Fagus* populations. *Aesculus* had no trees recorded in the 30+ m category and fewer trees in the 25-30 m category. Indeed in the Kew data, *Aesculus* was seen not to have any specimens greater than 20 m. *Acer* and *Quercus* appeared as the next smallest genera, though the damaged trees in both the F.C. and Kew surveys recorded trees of greater than 30 metres in height. The Essex data showed *Quercus* to have a greater population of trees over 15 m than *Tilia*, casting doubt on the previous findings. On reference to the F.C. and Kew histograms, crown damaged trees and undamaged trees indeed both showed *Tilia* to have a marginally smaller population of above 15 metres in height. The breakdown of this population was not possible with the Essex data, but in the F.C. data the splitting of this group into groups 15-20 m, 20-25 m, 25-30 m, and 30+ m, clearly showed *Fagus* to have a greater proportion of taller trees. A similar phenomenon was seen when comparing *Fagus* with *Tilia*. The Essex data suggested that *Fagus* had a taller population than *Tilia*, but on the examination of the upper height brackets in the F.C. and Kew data it was found that *Tilia* had the highest population. Both the *Tilia* and the *Fagus* had taller populations than *Quercus*, resulting in a rank order of:- *Tilia*, *Fagus*, *Quercus*, *Acer*, *Aesculus*.

The Essex data showed the entire tree population to be much smaller than in either the F.C. or Kew, with less than 10% of the total population above 15 m. This compared to the F.C. and Kew which have approximately 80% of their population greater than 15 m. In particular the Essex data highlighted *Malus*, *Sorbus* and *Prunus* which had 90% of their population under 10 metres.

The height distribution of *Pinus* and *Cedrus* was also considered (Fig. 3.12). *Cedrus* was found to be generally taller than *Pinus*, and on the whole slightly smaller than the major broadleafs with the exception of *Aesculus*. Neither genus recorded trees of 30 m or above.

The F.C. data when split into the three subsets, immediately revealed an interesting point (Fig. 3.9). The fallen trees and the crown damaged trees both had a similar distribution of tree heights. The undamaged trees however had a surprisingly small number of trees within the 15-20 m group. This small group was reflected throughout the major tree genera of the undamaged trees, but not the fallen or crown damaged groups. Either all trees of this particular height incurred some damage in high winds, or there was an anomaly in the data. Cutler, Gasson and Farmer (1989) suggested that trees of approximately 18 m, in their prime were more vulnerable to damage, however the F.C. results would have almost ever tree within this height bracket to be damaged in strong winds.

Closer examination of the F.C. data revealed that the values given for the aerial parameters of the trees in the undamaged data subset were actually estimations rather than accurately measured values. If the values were merely estimated, the graphs produced would still be expected to show a reasonable degree of scattering, indeed the estimations would probably have passed unnoticed. This was not the case. Values were seen to collect on a few specific values on the graph axes. It would appear that rather than estimating values for a tree, the tree was assigned one of a small number of preselected values, all be it perhaps closest to its actual measurement. The tree heights, for example, were either 9 m, 15 m, 21 m, or 27 m, and trunk diameters were 40 cm, 75 cm, 125 cm, or 160 cm. These values were selected by the F.C. presumably after some initial analysis had been undertaken on the fallen and crown damaged subsets. The decision to estimate values was most probably to reduce the time involved in surveying, but the reason for the allocation of these specific values remains unclear. The F.C. did decide however, at some stage in their analysis, to split the tree heights into those above and below 18 m. For the F.C. analysis the data accuracy may prove to be sufficient, but for more detailed comparisons, the shortcomings present a problem, and greatly reduce the value of this data set. All the results involving the F.C. undamaged data set must be interpreted with caution.

The comparisons of tree heights and the height range at which most were susceptible to wind damage, were restricted, but the three F.C. data sets were still compared to extract some height information. The differences between the sets were not striking, (excepting those trees 15-25 m). There were however, no trees above 30 m present in the undamaged data. The fallen trees had 8% within this range and the crown damaged had 5%. The tallest trees were therefore most likely to fall rather than suffer crown damage, or remain unscathed.

When considering trees above 25 m tall, the F.C. fallen trees had a greater proportion than the crown damaged trees, but less than the undamaged trees. This trend was also seen when considering trees above the 20 m height, though the undamaged tree data must be viewed with great caution in this case.

The heights of the fallen trees in the Kew data compared favourably with the F.C. data, showing a similar proportion of trees within each height class. It was specifically noted that approximately 5% of trees above 30 m in height, were uprooted.

The Essex data appeared to have a bias towards the smaller tree with less than 10% above 15 m (Fig. 3.11). Both the F.C. and Kew data showed over 70% of their population to be above this height.

When the F.C. data was considered as a whole, it was observed that those trees which fell contained more of the tallest trees, whilst no undamaged tree was recorded over the height of 30 m. Of the major genera, this trend appeared for *Fagus* and *Tilia*. However *Quercus*, *Aesculus*, and *Acer* were seen to have smaller heights in the fallen subset than in either the undamaged or crown damaged subsets respectively.

It was interesting to note that the subset of trees that fell, in both *Pinus* and *Cedrus*, had fewer trees over 25 m than either the crown damaged or the undamaged subsets (Fig. 3.12).

All these observations suggested that the type of tree failure was as much or more a function of genera as it was of tree height.

3.3.3 Aerial parameters of trees

3.3.3.1 Introduction

When considering more than one of the trees' parameters at once, positive relationships between the crown spread and trunk diameter, and also between the crown spread and tree height were found. Figures 3.13 and 3.14 illustrate this in the F.C. fallen subset. The plotted points showed a degree of scattering with the fitted regression lines accounting for approximately 46% and 37% of the variation respectively. The scattering was least when crown spread and trunk diameter were considered. This finding was also repeated throughout the 3 major F.C. of subsets, and so crown spread versus trunk diameter was the parameter selected to describe the aerial structure of the tree.

Crown spreads were recorded by the F.C. with a maximum value of almost 40 m, and an average of approximately 14 m, depending on the subset. Trunk diameters reached almost 2 m, with a average however of approximately 80 cm. The Kew data produced similar figures, but the average values from the Essex database tended to be much smaller.

3.3.3.2 Differing tree structure between fates

T-tests revealed significant differences between the F.C. fallen and F.C. undamaged data sets, but not between either set and the F.C. crown damaged data set. The fallen trees showed a greater increase in trunk diameter with increasing crown spread (Fig. 3.15). The fallen trees also showed a greater trunk diameter for any specific crown spread than the undamaged tree. The crown damaged trees however had the greatest trunk diameter per crown spread.

Caution must be taken however when considering the F.C. undamaged data set, due to the anomaly described earlier (Section 3.3.2).

In the comparison of crown spread and height, the F.C. fallen trees showed no significant differences from either the F.C. undamaged or the F.C. crown damaged trees. Nor were the undamaged trees seen to differ significantly from the crown damaged trees.

Quercus was selected as one of the most abundant genera and regression lines were drawn for each fate of the F.C. *Quercus* (Fig. 3.16). The fallen *Quercus* showed a slightly lower increase in trunk diameter than the undamaged *Quercus,* unlike the complete F.C data set. The fallen *Quercus* did appear however to have larger trunk diameters for crown spreads than the undamaged tree. The crown damaged tree again had the largest trunk diameter for any specific crown spread for the *Quercus*. The t-test however, showed there to be no significant difference between these results for the *Quercus*.

The F.C. fallen *Tilia* was found to differ significantly from the undamaged *Tilia.* The trunk diameter was again found to increase more with increasing crown spread for the fallen *Tilia* than the undamaged *Tilia.*

The Kew fallen trees showed no significant differences from the Kew standing data, nor from the F.C. trees when they were considered as the 3 subsets experiencing the differing fates (Tables 3.3 and 3.4). The Kew fallen *Tilia* however, were seen to differ significantly from the F.C. fallen *Tilia* .

Of the conifers, fallen *Cedrus* also revealed significant differences between itself and both the undamaged and crown damaged subsets (Table 3.26). *Pinus* showed no differences within the genus (Table 3.27).

3.3.3.3 Differing tree structure between genera and species

Comparison made between selected genera revealed no significant differences in aerial structure except in the case of the F.C. fallen *Tilia*. This was found to be significantly different from the F.C. fallen *Quercus* and the F.C. fallen *Aesculus.* In both these cases the fallen *Tilia* displayed a significantly greater increase in trunk diameter for any increase in crown spread than the other data subsets (Fig. 3.17).

The conifers, *Pinus* and *Cedrus* revealed no significant differences in the crown spread/ trunk diameter relationship from the larger broadleaf genera, with the exception of the fallen *Cedrus* subset which was seen to differ from all the broadleaf trees and the *Pinus* as well.

Comparisons were made between selected species, to investigate whether any trends in the results were hidden by grouping data into genera. This could arise if the species within a specific genera varied greatly in terms of physical form and appearance. *Quercus robur* (English Oak) and *Fagus sylvatica* (common Beech) were selected, but the analysis revealed no significant differences, just as in the comparison of their respective genera (Table 3.18). The F.C. however did suggest that *Tilia platyphyllos* (larged-leaved Lime) is more vulnerable to damage than *Tilia vulgaris* (common Lime) (Gibbs and Greig 1990), however this finding was not associated with any differences in the trees physical parameters.

3.3.3.4 The Essex data

The Essex data sets, street, school, and 'other' sites showed no significant differences when the aerial structure was considered. This inferred that these data sets could be amalgamated and considered as a single information source, confirming the idea that the initial separation was arbitrary, solely for the purpose of ease in the data collection.

The tree forms of the smaller Essex trees were compared with each other and *Prunus* and *Malus* showed no significant differences between each other. The *Sorbus* however, showed a significant difference with the *Prunus* and not *Malus*.

When these genera were compared with selected larger tree genera in the F.C. data sets *Prunus* and *Malus* displayed significant differences from the F.C. undamaged *Quercus*, *Fagus*, *Tilia*, and *Aesculus*. The *Sorbus* also differed from the F.C. undamaged *Tilia*, but not the *Quercus*, *Fagus* or *Aesculus* (Table 3.19).

Comparisons were also made with the F.C. fallen and crown damaged data sets. *Malus*, *Prunus* and *Sorbus* were all seen to differ significantly from the fallen *Fagus* and *Tilia*, but not from the fallen *Quercus* and *Aesculus*.

The *Malus* and *Prunus* were found to differ from the crown damaged *Tilia*, and the *Malus* also from the crown damaged *Aesculus*. Apart from these, there were no significant differences with the crown damaged F.C. trees.

3.3.4 Subterranean parameters of trees

3.3.4.1 Introduction

Up to this point the tree roots have largely been ignored. The F.C. fallen tree subset provided an opportunity to examine various aspects of rooting. Root-plate spread and rooting depth were selected and comparisons made between genera. It should be noted that the values were not the actual rooting spread or depth, but the respective value which each retained on uprooting. The entire root system would have been far greater (Section 2.4.1), but it was assumed that the uprooted root-plate was of greatest significance when considering the structural stability of the tree.

Maximum and mean values were calculated for the most common genera (Table 3.33). *Fagus* appeared to have the largest root-plate spread (9 m), with *Tilia*

(7 m) and *Cedrus* (6 m) next. *Fagus* also had the greatest mean root-plate spread (4.23 m). The deepest roots were found to be 1.8 m, a depth shared by *Quercus*, *Tilia* and *Fagus*, with *Quercus* having the greatest mean depth (0.83 m). Kew found the majority of roots to form a root-plate radius of less than 4m, and less than 2 m in depth (Cutler, Gasson and Farmer 1989).

Graphs of subterranean parameters did not show scatter patterns like those observed when the aerial parameters were considered. Instead the points were localised along the axes, appearing only on the whole metre value points for the root-plate diameter, and on the 0.1 metre lines of the root depth axis (shown for *Quercus*, Fig. 3.18).

3.3.4.2 Root-plate spread and rooting depth

All genera showed positive relationships between root-plate spread, and root depth except *Cedrus*. The regression lines and associated t-tests revealed a complex picture for root-plate diameter versus root depth (Fig. 3.19), with significant differences between some genera and others (Table 3.35). *Cedrus* was most significantly different from all the other genera except *Pinus* (another conifer). *Fagus*, and *Aesculus* were observed to have similar slopes as did *Pinus* and *Quercus*, though the only significant differences recorded (excluding *Cedrus*) were between *Tilia* and both *Quercus* and *Pinus*.

It was also observed that the values of percentage variance accounted for by the regression lines were greatly reduced compared with those of the aerial parameters (the maximum value accounted for was 29.5%, with other values lower down to a point where residual variance exceeds the variance of the Y variate), though it must also be noted that the subsets involved were also greatly reduced.

3.3.4.3 Root-plate spread and trunk diameter

The relationship between trunk diameter and root-plate spread was positive without exception (Fig. 3.20). T-tests again revealed differences between genera, but varying from those described between root depth and spread (Table 3.34).

Quercus, *Tilia*, and *Pinus* showed no significant differences in root-plate diameter with trunk diameter regression lines. Significant differences were recorded between these and *Aesculus*, *Fagus* and *Cedrus* (with the exception of *Pinus* and *Fagus*). *Aesculus* and *Cedrus* (with the smallest increase in trunk diameter with increasing root-plate spread), both differed significantly from *Fagus* but not from each other (Table 3.34).

3.4 Discussion

3.4.1 Genus composition of tree population

The difference in genus population composition of the data sets described in the results (Section 3.3.1) may be partially assigned to differences in the type of survey and its target areas. The F.C. data was of park land trees, which may either have been planted or self-seeded, perhaps left after woodlands have been cleared for farming land. It is likely that the majority were self-seeded, and it is also noticeable that three of the major genera have tree species which are native English trees (*Fagus*, *Quercus*, and *Tilia*). The *Acer*s comprised predominately of *pseudoplatanus* (Sycamore) and *platanoides* (Norway Maple) though not native species were introduced to Britain just after the native tree cut off date, when Britain became an island.

Betula, which was found present in reasonable numbers in the Kew and Essex data, was almost absent from the F.C. data. This may again be allotted to the survey type and area. *Betula* is generally a small tree, which, though a native and invasive pioneer species, does not tolerate grazing to a great extent, nor is it a tree which is valued for its timber or aesthetic properties on a park land scale. Within the F.C. statement of survey details it was also stated in the choice of sites that there must be a minimum of 50 trees over 6 metre tall and that 30% must be significantly damaged. *Betula* may therefore have been almost absent from the park lands as suggested by the survey, or deemed not worthy of inclusion, being of a small height. Indeed only two out all the trees surveyed by the F.C. were less than 5 metre high. The Essex database however, surveyed trees of much smaller sizes, with a third being below 5 metres.

The Kew data also showed large proportions of native *Fagus* and *Quercus*, but also had a large selection of 'other' species. Many of the survey sheets were completed at Kew gardens, and probably showed a bias towards a greater number of perhaps ornamental and exotic species. There may also have been a tendency for other persons involved to select the more unusual or impressive trees for study. The Kew trees were generally single urban/ roadside trees and a large proportion were therefore probably planted. Tree selection may not have been limited specifically to native trees, and a greater variety is therefore expected.

The Essex database showed an even greater number of 'other' trees. This may be partly attributed to the major tree selection of both the F.C. and Kew surveys, but also to the deliberate selection of smaller tree varieties for ornamental use in streets and enclosed public areas. Larger trees in confined space, especially close to the living environments can cause social problems of shade and shed leaves. *Malus*, *Prunus*, *Crataegus* and *Sorbus* feature greatly in the Essex data. Their absence from the F.C. and Kew data may be for reasons of height described earlier, or perhaps because they are particularly wind firm species, though this latter reasoning would not excuse their low numbers in the F.C. undamaged data set. *Crataegus* was perhaps the most surprising, being a common plant in woodlands and farm land areas.

When considering the fate of the minor genera, it must be noted that conclusions are being drawn from a relatively small number of examples. The statistical importance must be viewed with caution, though trends may be highlighted and should not be ignored. The recorded damage of *Fraxinus* and *Carpinus*, for example, being solely crown damage, may be indicating great root stability, and the suitability of these genera to be planted in sites were uprooting would be particularly undesirable.

The great incidence of the *Betula* to be damaged may be due to the vulnerability of the species, or perhaps, due to reasons described earlier, only the damaged specimens attracted the attention of the surveyors.

The 'other broadleafs' also were seen to have a high damage record which may perhaps again be accounted for by fallen specimens attracting attention. Alternatively if the results genuinely reflect the population, they may be indicating that the rarer, perhaps introduced, or ornamental species are less wind firm and less able to cope with the environmental conditions, and are therefore less suitable trees to plant. The first suggestion is thought to be more credible due to the large proportion of 'other trees' in the Essex database, and the relatively small number in the F.C. fallen trees subset.

3.4.2 Tree heights

Few small trees (less than 5 m) were recorded, particularly in the F.C. survey. This reflected a lack of young trees observed. Due to the nature of the F.C. sites, established park lands, trees tended to be semi-mature, mature or over-mature. From this, it could not be assumed that young trees are not damaged by strong winds. However, it may be assumed that a windblown young tree is likely to cause less damage than a larger mature tree due simply to its smaller size and weight.

The F.C., Kew and Essex tree heights may be compared with observations made by Mitchell and Wilkinson (1989) (Fig. 3.21). Height of tree species have been recorded for trees at 20 years of age and also an ultimate height gained for the species when grown in favourable conditions. It should be noted that these are tree species not genus, however selection was made for the most popular species present within the genus where possible. Heights were not given for *Malus sylvestris* (Crab Apple), so *Malus* 'John Downie' was substituted. At 20 years, *Acer pseudoplatanus* followed by *Tilia europea* (European Lime) and *Quercus robur* were seen to be the tallest species, followed by *Aesculus hippocastanum* (Horse Chestnut) and *Fagus sylvatica* respectively. Ultimate heights however show the *Tilia* (46 m) to be taller than the *Fagus* (40 m), the *Aesculus* (38 m), and the *Acer* (35 m), with the *Quercus* (26 m) much shorter.

The survey data of *Fagus* and *Tilia* showed good agreement with these ultimate heights, though maximum heights were not recorded. In the surveys the *Aesculus* were seen to be smaller than observed by Mitchell and Wilkinson but this may be due to the species not being a native tree. Originating from Greece, *Aesculus hippocastanum* thrives in deep rich valley soils (Mitchell and Wilkinson 1989), and may not perhaps achieve ultimate growth in the SE England.

The *Quercus* recorded in the surveys were found to grow to heights greater than 26 metres, the ultimate height of *Quercus robur*. Although *Quercus robur* is the most common species in the UK. particularly on the heavy clays of the SE, it is not the only species. Taller species *Quercus petraea* (Sessile Oak), and *Quercus cerris* (Turkey Oak), for example must be present in the surveys boosting the heights recorded for the genus. The smaller height of the *Quercus robur* does however explain the high percentage of *Quercus* between the heights of 10-25 metres.

The *Prunus* and *Malus* recorded in the Essex database showed very good correlation with the ultimate heights of 10 metres.

The *Sorbus* found in the Essex data appeared to be rather small, with over 95% being less than 10 metre in height. Investigation of the age of the trees (Fig. 3.22) provided a reason for this anomaly. Whilst most species had between 40% - 50% of the population in the young and semi-mature age classes, *Sorbus* was shown to have almost 80% of its population less than mature. This species, though native to the chalk downlands of SE England, has only recently become a popular tree to plant. Its characteristics could therefore not be assessed as to whether it would be susceptible to wind damage, and in what form, once it became mature.

The *Acers*, though observed to contain a number of tall trees, tended to be comprised of a shorter population with a similar height distribution to *Quercus* and *Aesculus*. This could perhaps be explained again by *Acers* having a young population. *Acers* may therefore potentially be taller trees than the *Quercus* and *Aesculus*.

The height distribution of *Pinus* and *Cedrus* was also in agreement with their respective ultimate heights in Mitchell and Wilkinson (1989).

3.4.3 Aerial parameters of trees

The t-tests revealed significant differences in the aerial parameters of specific groups of trees (Section 3.3.3), which will now be further discussed.

3.4.3.1 The case of the fallen *Tilia*

The results of the comparison of the aerial parameters of the three F.C. data sets show a significant difference between the fallen and undamaged data sets. Following the subsequent investigation of individual genera it appears that *Tilia* alone may be responsible for this trend, particularly as *Tilia* comprises 35% of the F.C. fallen tree subset. The F.C. fallen *Tilia* subset was observed to have a much steeper fitted regression line when compared with other sub groups (both different fates and different subsets), including the Kew fallen *Tilia*.

Reasons have been sought to explain this finding. Variation, either due to biological reasons or external exposure or growing conditions, was rejected as a reason, because 48.3% of the variation of scatter was accounted for by the fitted regression line. This is a greater amount than in either the undamaged (41.6%) or crown damaged *Tilia* (31.0%), or even the fallen *Quercus* (39.6%) for example.

One hypothesis for this result relates to a finding of the F.C. in which they report an increase in the occurrence of damage with increasing trunk diameter (Gibbs and Greig 1990). Whilst this was not directly investigated in this analysis, damage occurrence was initially only found to be closely linked with the tallest group of trees. As height was found to be closely correlated with trunk diameter, it may be assumed that the trees of greatest trunk diameter would be most susceptible to wind damage.

Tilia perhaps has a growth habit particularly different from the other most abundant tree genera. Early in its life the *Tilia* perhaps achieves heights close to its maximum, and from then onwards growth is better represented by the increase in trunk diameter. The occurrence of damage could then be related to an increasing stiffness in the trunk, due to its increased diameter. The F.C. finding of increased damage with increasing trunk diameter would then support this hypothesis.

However the tree heights given by Mitchell and Wilkinson do not support the theory of fast early growth by the *Tilia.* At 20 years, the height of *Tilia* is similar to both *Fagus* and *Quercus*, and even lagging behind the *Acer* (Fig. 3.21).

This theory of rapid early growth, does not explain the difference between the F.C. and Kew data either.

The F.C. also reported that allocated crown structure scores appeared to have no correlation with the number of wind blown trees. Crown spread is a function of crown structure, and was found to be correlated with trunk diameter. This does not support the F.C. theory of increased damage occurrence with increased trunk diameter.

The fallen *Cedrus* displayed similar differences when its line of best fit was compared, however as there were only six members in the subset, the significance of this result is thus small. The fallen *Tilia*, described above, could not be disregarded in this way as the numbers involved were far greater, 116 fallen *Tilia* 60 crown damaged and 668 undamaged.

3.4.3.2 The smaller tree genera

The crown spread/ trunk diameter regressions of *Malus* and *Prunus* when compared with the broadleaf genera, showed some significant differences (Fig. 3.23). In this incidence however, the lines of best fit were observed to approximately parallel but separated along the trunk diameter axis of the graph. This suggested a difference in the form of the trees at every stage in their growth, that is the trunk diameter of a *Malus* or *Prunus* will be smaller than that of the *Quercus*, *Tilia*, *Aesculus* or *Fagus* for any given crown spread.

3.4.3.3 The F.C. Anomaly

As the t-tests revealed no significant differences between paired parameters (height and crown spread, and trunk diameter and crown spread), between the F.C. undamaged and crown damaged trees it suggests that the estimated undamaged tree values provided reasonably accurate lines of best fit.

3.4.4 Subterranean parameters of trees

The structural tree root systems appeared to be more variable than the crown, in that more significant differences were found between genera. However, these results inspire less confidence than the aerial parameters as the two sets of results gained, were less consistent. Also the percentage variance accounted for by the regression lines was often minimal.

The measurement of root-plate spread and depth to the nearest metre or tenth of a metre highlights the difficulty in measuring these parameters. The physical process of measuring is not the problem in this instance, but rather the actual definition of the edge of the root-plate, and its depth.

The results gained for root-plate spread and depth were structural components only and cannot therefore be compared with the figure describing total rooting depths and spreads (Section 2.4.1), nor be used as guidelines for safe working distances from trees (for the safety of the tree), during building constructions or ground excavations. The relatively shallow depth does however support the hypothesis of no major tap root.

It may have been interesting to model the trees' wind interception area with the counteracting root/ soil volume. However the F.C. (Gibbs and Greig 1990), found no significant differences between the sail areas of the more predominant genera.

3.4.5 Soil types and its effect on tree stability

Soil types have not been analysed in this chapter because information is available only from the F.C. and Kew, whom have both drawn and published their own findings on this topic. However their results appear to be in contradiction. The F.C. experienced most uprooting on brown earth (Gibbs and Greig 1990), though *Quercus* was observed to be less stable on sand. Kew found sand to be the most frequently occurring soil type (Cutler, Gasson and Farmer 1989). It would appear that these finding greatly reflect the nature of the sites surveyed. The F.C. sites spread over only a narrow band of the SE England, concentrated on areas of the London clays. The Kew data arises from a far greater range of soil types. Cutler, Gasson and Farmer (1990) also concluded however, that plantations were especially vulnerable on clay soils, despite there being a tendency to plant on sandy soils. This supports the findings of the F.C.. These results stress the complexity of tree fall, allowing no positive conclusions to be drawn on which soil types rend trees particularly vulnerable. Moisture content measurements at the time of uprooting may have improved the understanding of this subject, but it was not possible to record this parameter until substantial changes were likely to have occurred.

3.5 Conclusion

A large amount of useful information has been gathered in the form of the three databases. All have specific advantages and disadvantages which have been described in the previous discussion. Credibility is added to these survey results by their good correlation of heights of particular genera when they are compared with the findings of Mitchell and Wilkinson (1989).

For the comparison of whether species are wind firm or not, the most comprehensive data set was the F.C. data with the undamaged, damaged, and fallen trees all recorded, though it would have been of greater use if the aerial parameters of the undamaged trees had been measured and not estimated. Comparisons were drawn from the Kew data particularly when seeking confirmation of trends of the fallen tree subset. The Essex data had to be consulted when reference was made to the total tree population, and specific tree parameters of undamaged trees, because of its size and the large quantity of information it contained. With these limitations born in mind the following broad conclusions can be drawn.

Park lands are comprised predominately of five genus :- *Acer*, *Aesculus*, *Fagus*, *Quercus*, and *Tilia*. Of these genus the *Acer* was seen to be the least susceptible to wind damage, though this may have been due to a bias towards a younger, and smaller population. *Fagus* and *Tilia* were found to be prone to uprooting in the wind, whilst *Aesculus* and *Quercus* appeared more prone to crown damage. It appeared that the particular fate of the tree was determined more by genus than size, though size was a factor, related to the genus, in whether the tree was damaged at all. Of the more minor species, *Populus*, *Fraxinus*, *Carpinus* and *Cedrus* are most prone to crown damage, whereas *Platanus* and *Pinus* have a greater tendency to uproot. Of these genus, *Populus* and *Fraxinus* are the most likely to incur damage.

The composition of the population of trees growing in closer proximity to areas of greater public access consists of a wider range of tree species, with less dominance of any particular species. Exotic and ornamental species are planted for decoration and variety, often with a bias to the smaller growing species. *Malus*, *Prunus*, *Crataegus* and *Sorbus* are found to be the most commonly occurring genera of the smaller tree. Incidence of the uprooting or crown damage of these trees was not recorded in the surveys largely because of their absence in the F.C. survey. Investigation of their wind firmness is therefore inconclusive.

Fagus and *Tilia, which* were found most prone to uprooting, were the tallest genus, whilst *Aesculus* and *Quercus*, slightly smaller trees, suffered more from crown breakage.

Trees of all sizes were seen to suffer crown damage and/ or uprooting in strong winds. However similar trees spanning all heights below 30 m were seen to remain unscathed in high winds. The differences between the number of trees in each height class was very little and unlikely to be significant with perhaps the exception of the trees over 30 m high. A greater tendency for trees of heights of 30 metre and above to fall, or at least receive crown damage was seen. The major genera all reflected these trends with trees present in each height class, and experiencing all the different fates. The greater proportion of small trees in the Essex data, and relative lack of these trees in the F.C. and Kew data suggested that the smaller tree was less susceptible to damage.

In conclusion, it appears that tree height is not a critical factor in the survival of a tree in strong winds, with perhaps exceptions at the upper and lower extremities. The tallest trees over 30 m are found to be particularly vulnerable to wind damage, whilst the smallest trees, below 10 m, incur damage less frequently.

Tree size for any particular tree may be described in terms of height, as no significant or consistent differences were revealed between different genera in the relationship of height with either crown spread, or trunk diameter, with the exception of the F.C. fallen *Tilia*. Similarly differences in trees which fell and those which remained standing, or undamaged show no differences in physical structure other than general size, described as height in the previous paragraph.

The surveys show differences in various parameters, heights for example. These can be attributed however to specific genera, whose numbers vary in the proportion to the total population in each data set. These differences can be accounted for by the differing nature of the sites surveyed. The essential parameters for any specific genus were found consistent throughout all the data sets.

Tables : Chapter 3

T-tests between regression lines of data sets

	Data set 2
Data set 1	t-value df value * significant or - not significant

Example table : the numbers represent the t value and the df value

	Street	Other site
School	0.95 3818.9 -	1.33 2038.9 -
Street	-	0.42 2911.7 -

Table 3.1 Essex data - trunk diameter and crown spread

	F.C. Fallen	F.C. Crown damaged
F.C. Undamaged	1.97 4280 *	1.20 885.4 -
F.C. Fallen	-	0.76 638.6 -

Table 3.2 F.C. data - trunk diameter and crown spread

	Kew crown damaged
Kew fallen	0.42 11.3 -

Table 3.3 Kew data - trunk diameter and crown spread

	F.C. fallen
Kew fallen	0.90 573.39 -

Table 3.4 Kew fallen and F.C. fallen trees - crown spread and trunk diameter

	F.C. fallen *Quercus*	F.C. crown damaged *Quercus*	F.C. undamaged *Fagus*	F.C. undamaged *Tilia*	F.C. undamaged *Aesculus*	Kew fallen *Quercus*
F.C. undamaged *Quercus*	0.81 104.0 -	1.31 352.2 -	0.19 752.21 -	0.90 1180.7 -	0.16 774.6 -	0.06 193 -

Table 3.5 F.C. undamaged *Quercus* and other fates and genera - crown spread and trunk diameter

	F.C. crown damaged *Quercus*	F.C. crown damaged *Fagus*	F.C. crown damaged *Tilia*	F.C. crown damaged *Aesculus*	Kew fallen *Quercus*
F.C. fallen *Quercus*	0.37 154.8 -	1.84 95.0 -	3.53 160.6 *	0.38 15.0 -	0.62 145.6 -

Table 3.6 F.C. fallen *Quercus* and other fates and genera - crown spread and trunk diameter

	F.C. crown damaged *Fagus*	F.C. crown damaged *Tilia*	F.C. crown damaged *Aesculus*	Kew fallen *Quercus*
F.C. crown damaged *Quercus*	0.79 111.1 -	1.87 116.0 -	0.95 264.5 -	1.01 250.9 -

Table 3.7 F.C. crown damaged *Quercus* and other fates and genera - crown spread and trunk diameter

	F.C. fallen *Fagus*	F.C. crown damaged *Fagus*	F.C. undamaged *Tilia*	F.C. undamaged *Aesculus*	Kew fallen *Fagus*
F.C. undamaged *Fagus*	1.23 84.6 -	0.31 82.5 -	0.67 807.3 -	0.33 640.1 -	0.12 132.5 -

Table 3.8 F.C. undamaged *Fagus* and other fates and genera - crown spread and trunk diameter

	F.C. crown damaged *Fagus*	F.C. fallen *Tilia*	F.C. fallen *Aesculus*	Kew fallen *Fagus*
F.C. fallen *Fagus*	1.23 90.5 -	1.73 133.9 -	1.13 15.8 -	1.11 111.5 -

Table 3.9 F.C. fallen *Fagus* and other fates and genera - crown spread and trunk diameter

	F.C. crown damaged *Tilia*	F.C. crown damaged *Aesculus*	Kew fallen *Fagus*
F.C. crown damaged *Fagus*	1.03 105.9 -	0.06 111.4 -	0.16 112.2 -

Table 3.10 F.C. crown damaged *Fagus* and other fates and genera - crown spread and trunk diameter

	F.C. fallen *Tilia*	F.C. crown damaged *Tilia*	F.C. undamaged *Aesculus*	Kew fallen *Tilia*
F.C. undamaged *Tilia*	2.77 189.9 *	0.55 84.9 -	1.03 836.4 -	1.23 18.53 -

Table 3.11 F.C. undamaged *Tilia* and other fates and genera - crown spread and trunk diameter

	F.C. crown damaged *Tilia*	F.C. fallen *Aesculus*	Kew fallen *Tilia*
F.C. fallen *Tilia*	1.58 134.7 -	2.56 18.2 *	2.76 27.7 *

Table 3.12 F.C. fallen *Tilia* and other fates and genera - crown spread and trunk diameter

	F.C. crown damaged *Aesculus*	Kew fallen *Tilia*
F.C. crown damaged *Tilia*	1.06 117.1 -	1.41 32.6 -

Table 3.13 F.C. crown damaged *Tilia* and other fates and genera - crown spread and trunk diameter

	F.C. fallen *Aesculus*	F.C. crown damaged *Aesculus*	Kew fallen *Aesculus*
F.C. undamaged *Aesculus*	0.10 10.3 -	0.02 217.9 -	2.34 2.05 -

Table 3.14 F.C. undamaged *Aesculus* and other fates and genera - crown spread and trunk diameter

	F.C. crown damaged *Aesculus*	Kew fallen *Aesculus*
F.C. fallen *Aesculus*	0.07 14.8 -	2.31 2.2 -

Table 3.15 F.C. fallen *Aesculus* and other fates and genera - crown spread and trunk diameter

	Kew fallen *Aesculus*
F.C. crown damaged *Aesculus*	2.32 2.1 -

Table 3.16 F.C. crown damaged *Aesculus* and other fates and genera - crown spread and trunk diameter

	Kew fallen *Tilia*	Kew fallen *Fagus*	Kew fallen *Aesculus*
Kew fallen *Quercus*	0.74 24.7 -	0.05 164.4 -	2.31 2.1 -
Kew fallen *Tilia*	-	0.76 27.0 -	2.84 2.39 -
Kew fallen *Fagus*	-	-	2.29 2.1 -

Table 3.17 Kew fallen trees (selected genera) - crown spread and trunk diameter

	Essex *Fagus sylvatica*	F.C. undamaged *Quercus*
Essex *Quercus robur*	0.25 140.6 -	0.32 124.16 -
F.C. undamaged *Tilia*	0.12 132.54 -	0.19 725.21 -

Table 3.18 *Quercus robur*, *Fagus sylvatica* and F.C. undamaged *Quercus* - crown spread and trunk diameter

	Essex *Prunus*	Essex *Malus*	F.C. undamaged *Quercus*	F.C. undamaged *Fagus*	F.C. undamaged *Tilia*	F.C. undamaged *Aesculus*
Essex *Sorbus*	3.42 4025.7 *	1.57 3490.5 -	1.59 834.8 -	1.70 473.1 -	2.71 1038.7 *	1.32 490.9 -
Essex *Prunus*	-	1.62 4320.8 -	3.80 776.9 *	3.74 441.5 *	4.92 971.6 *	3.40 456.8 *
Essex *Malus*	-	-	2.62 889.2 *	2.66 500.3 *	3.71 1104.7 *	2.30 520.5 *

Table 3.19 Essex small genera and selected F.C. undamaged genera - crown spread and trunk diameter

	F.C. crown damaged *Quercus*	F.C. crown damaged *Fagus*	F.C. crown damaged *Tilia*	F.C. crown damaged *Aesculus*
Essex *Sorbus*	0.35 225.3 -	0.69 55.2 -	1.95 64.7 -	0.92 135.3 -
Essex *Prunus*	1.18 215.6 -	1.89 53.7 -	3.03 63.4 *	2.38 130.0 *
Essex *Malus*	0.41 233.0 -	1.28 56.4 -	2.48 65.9 *	1.63 139.5 -

Table 3.20 Essex small genera and selected F.C. crown damaged genera - crown spread and trunk diameter

	F.C. fallen *Quercus*	F.C. fallen *Fagus*	F.C. fallen *Tilia*	F.C. fallen *Aesculus*
Essex *Sorbus*	0.15 67.2 -	2.57 51.5 *	4.65 133.0 *	0.56 7.73 -
Essex *Prunus*	1.58 64.6 -	3.95 49.7 *	5.94 129.0 *	1.57 7.58 -
Essex *Malus*	0.86 69.2 -	3.23 52.9 *	5.25 136.1 *	1.06 7.85 -

Table 3.21 Essex small genera and selected F.C. fallen genera - crown spread and trunk diameter

	F.C. fallen	F.C. undamaged
F.C. crown damaged	0.24 741.5 -	0.11 1086.4 -
F.C. fallen	-	0.37 603.8 -

Table 3.22 F.C. data - crown spread and height

	F.C. fallen *Quercus*	F.C. fallen *Tilia*	F.C. fallen *Aesculus*	F.C. fallen *Fagus*	F.C. fallen *Cedrus*
F.C. fallen *Pinus*	1.48 17.32 -	1.15 20.14 -	1.03 17.00 -	0.15 18.08 -	3.59 10.70 *
F.C. fallen *Cedrus*	5.33 0.28 *	3.10 7.80 *	4.68 8.76 *	4.22 7.31 *	-

Table 3.23 F.C. fallen *Pinus* and *Cedrus* and selected F.C. fallen genera - trunk diameter and crown spread

	F.C. undamaged *Quercus*	F.C. undamaged *Tilia*	F.C. undamaged *Aesculus*	F.C. undamaged *Fagus*	F.C. undamaged *Cedrus*
F.C. undamaged *Pinus*	0.06 225.32 -	0.80 230.35 -	0.07 233.91 -	0.21 241.27 -	0.47 203.86 -
F.C. undamaged *Cedrus*	0.48 229.16 -	0.29 234.71 -	0.60 237.41 -	0.30 245.05 -	-

Table 3.24 F.C. undamaged *Pinus* and *Cedrus* and selected F.C. undamaged genera - trunk diameter and crown spread

	F.C. crown damaged *Quercus*	F.C. crown damaged *Tilia*	F.C. crown damaged *Aesculus*	F.C. crown damaged *Fagus*	F.C. crown damaged *Cedrus*
F.C. crown damaged *Pinus*	0.86 5.09 -	0.24 6.48 -	0.39 5.22 -	1.26 16.85 -	0.58 9.63 -
F.C. crown damaged *Cedrus*	1.83 13.99 -	0.48 19.02 -	1.27 14.49 -	0.41 5.89 -	-

Table 3.25 F.C. crown damaged *Pinus* and *Cedrus* and selected F.C. crown damaged genera - trunk diameter and crown spread

	F.C. undamaged *Cedrus*	F.C. crown damaged *Cedrus*
F.C. fallen *Cedrus*	4.87 6.41 *	3.02 12.80 *
F.C. undamaged *Cedrus*	-	1.02 13.16 -

Table 3.26 F.C. *Cedrus* - trunk diameter and crown spread

	F.C. undamaged *Pinus*	F.C. crown damaged *Pinus*
F.C. fallen *Pinus*	1.07 15.52 -	0.36 7.81 -
F.C. undamaged *Pinus*	-	0.36 4.95 -

Table 3.27 F.C. *Pinus* - trunk diameter and crown spread

	F.C. undamaged *Cedrus*	F.C. crown damaged *Cedrus*
F.C. fallen *Cedrus*	0.49 13.16 -	0.34 14.80 -
F.C. undamaged *Cedrus*	-	0.17 27.70 -

Table 3.28 F.C. *Cedrus* - trunk diameter and height

	F.C. undamaged *Pinus*	F.C. crown damaged *Pinus*
F.C. fallen *Pinus*	0.72 17.96 -	0.17 11.96 -
F.C. undamaged *Pinus*	-	0.44 7.93 -

Table 3.29 F.C. *Pinus* - trunk diameter and height

	F.C. fallen *Pinus*
F.C. fallen *Cedrus*	0.99 17.90 -

Table 3.30 F.C. fallen *Pinus* and *Cedrus* - trunk diameter and height

	F.C. crown damaged *Pinus*
F.C. crown damaged *Cedrus*	0.53 7.48 -

Table 3.31 F.C. crown damaged *Pinus* and *Cedrus* - trunk diameter and height

	F.C. undamaged *Pinus*
F.C. undamaged *Cedrus*	0.01 191.36 -

Table 3.32 F.C. undamaged *Pinus* and *Cedrus* - trunk diameter and height

	F.C. fallen *Quercus*	F.C. fallen *Tilia*	F.C. fallen *Fagus*	F.C. fallen *Aesculus*	F.C. fallen *Pinus*	F.C. fallen *Cedrus*
Max root-plate (m)	5.00	7.00	9.00	4.00	3.00	6.00
Mean root-plate (m)	2.77	3.40	4.23	2.29	2.55	4.10
Max root depth (m)	1.80	1.80	1.80	1.20	1.60	1.20
Mean root depth (m)	0.83	0.73	0.73	0.62	0.69	0.78

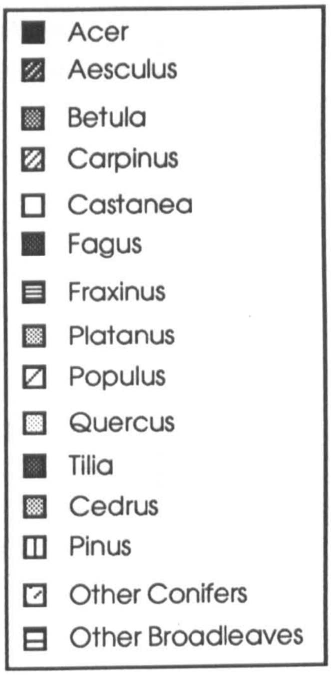
Table 3.33 F.C. fallen trees (selected genera) - root-plate spread and root depth

	F.C. fallen *Tilia*	F.C. fallen *Aesculus*	F.C. fallen *Fagus*	F.C. fallen *Pinus*	F.C. fallen *Cedrus*
F.C. fallen *Quercus*	0.09 108.58 -	4.06 35.51 *	2.08 111.88 *	0.12 17.94 -	3.74 12.65 *
F.C. fallen *Tilia*	-	4.86 21.20 *	2.75 149.59 *	0.07 12.35 -	4.05 9.77 *
F.C. fallen *Aesculus*	-	-	2.56 25.32 *	3.33 17.22 *	0.97 12.96 -
F.C. fallen *Fagus*	-	-	-	1.66 13.92 -	2.66 10.59 *
F.C. fallen *Pinus*	-	-	-	-	3.40 15.59 *

Table 3.34 F.C. fallen trees (selected genera) - root-plate spread and trunk diameter

	F.C. fallen *Tilia*	F.C. fallen *Aesculus*	F.C. fallen *Fagus*	F.C. fallen *Pinus*	F.C. fallen *Cedrus*
F.C. fallen *Quercus*	2.46 172.15 *	0.85 19.46 -	1.61 110.18 -	0.28 22.36 -	2.31 11.51 *
F.C. fallen *Tilia*	-	0.94 20.67 -	0.37 128.17 -	2.45 24.73 *	3.74 11.92 *
F.C. fallen *Aesculus*	-	-	0.53 31.29 -	1.01 19.32 -	2.61 16.12 *
F.C. fallen *Fagus*	-	-	-	1.71 40.41 -	3.18 16.47 *
F.C. fallen *Pinus*	-	-	-	-	2.02 12.86 -

Table 3.35 F.C. fallen trees (selected genera) - root-plate spread and root depth



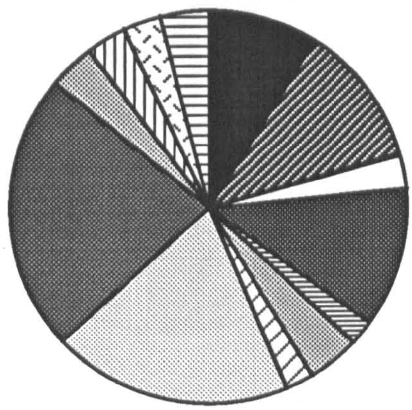


Figure 3.1 F.C. total tree population

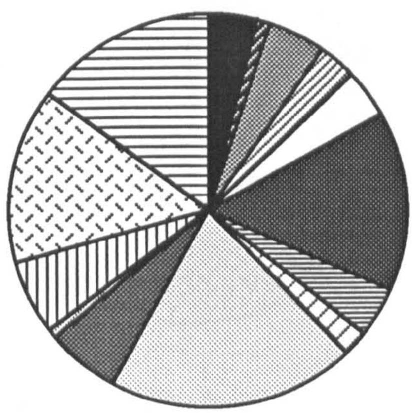


Figure 3.2 Kew total tree population

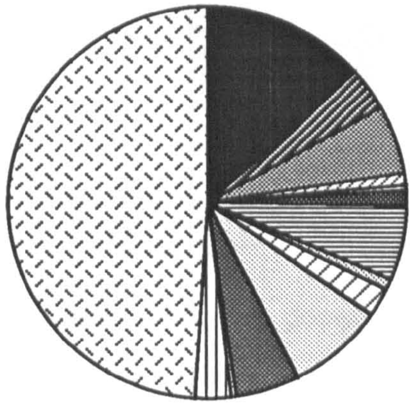
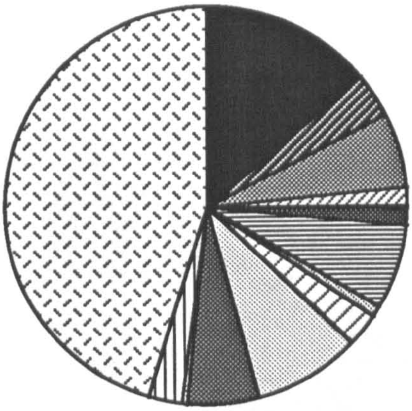
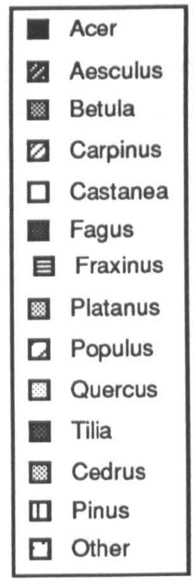
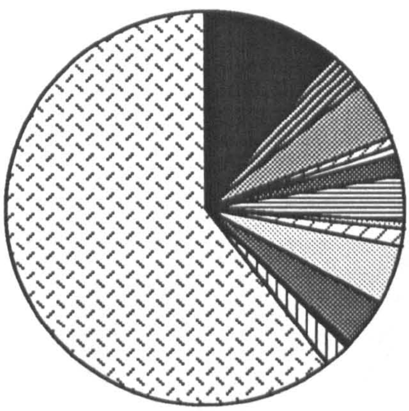


Figure 3.3 Essex total tree population

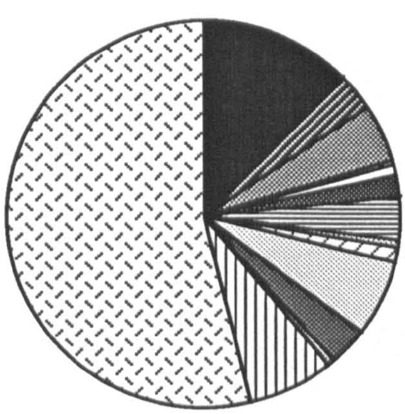




a) School tree population

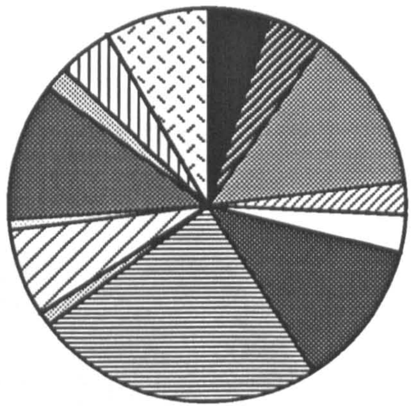


b) Street tree population

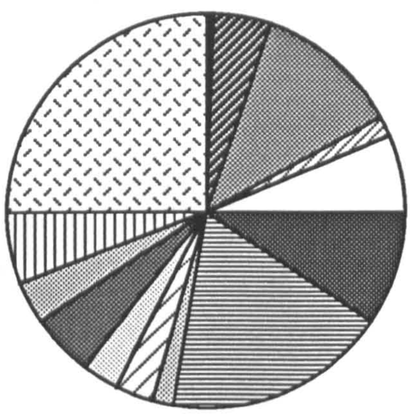


c) 'Other site' tree population

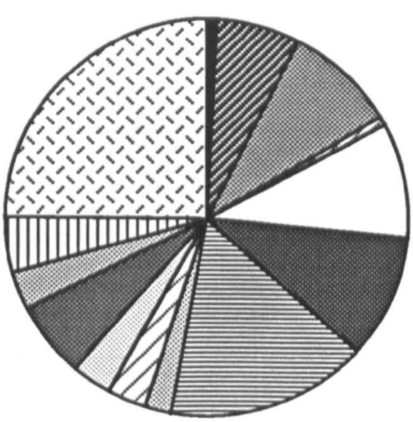
Figure 3.4 **Essex tree population in schools, streets and 'other sites'**



a) School sites

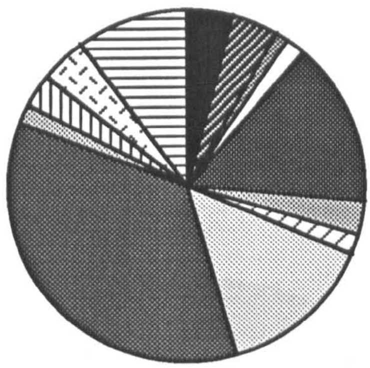


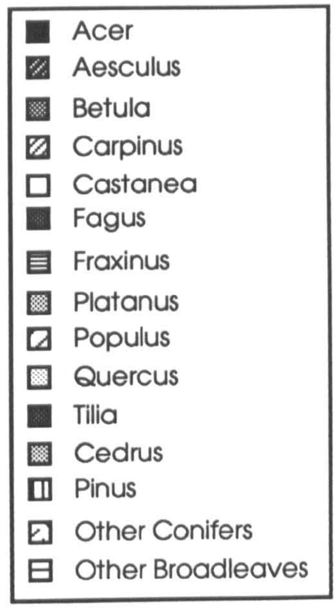
b) Street sites



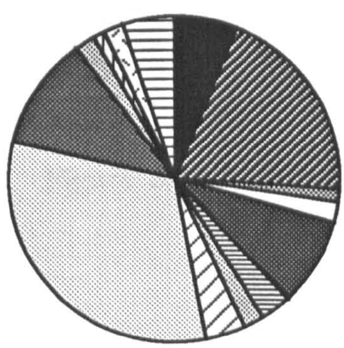
c) 'Other' trees on 'Other-site'

Figure 3.5 Genus population of Essex 'other' tree category

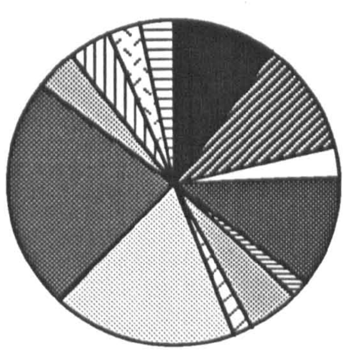




a) **F.C. trees - fallen**



b) **F.C. trees - damaged but standing**



c) **F.C. trees - undamaged**

Figure 3.6 The storm damage fate of F.C. tree population

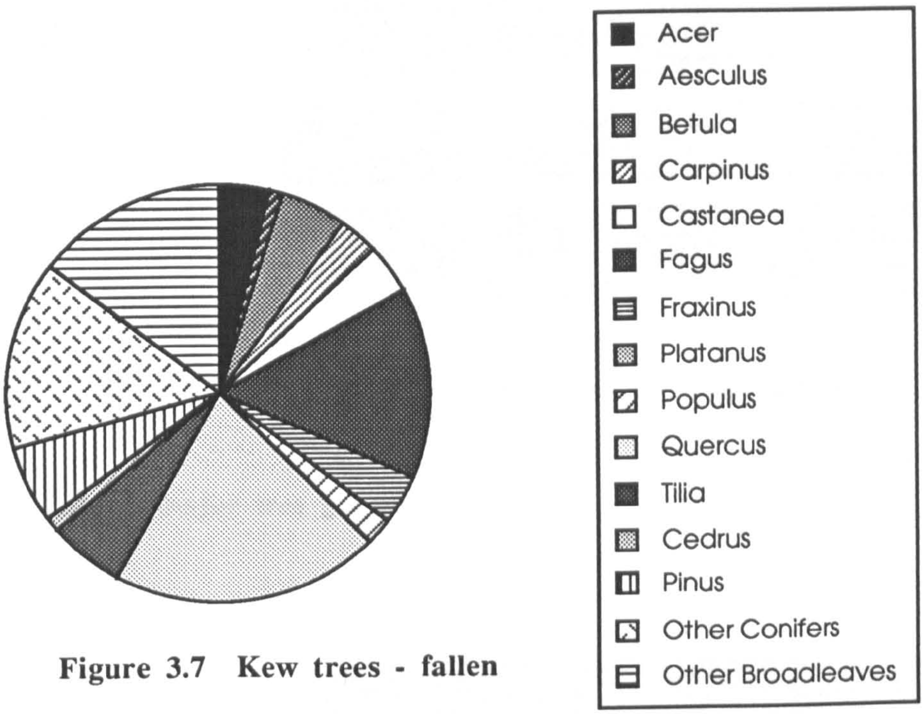
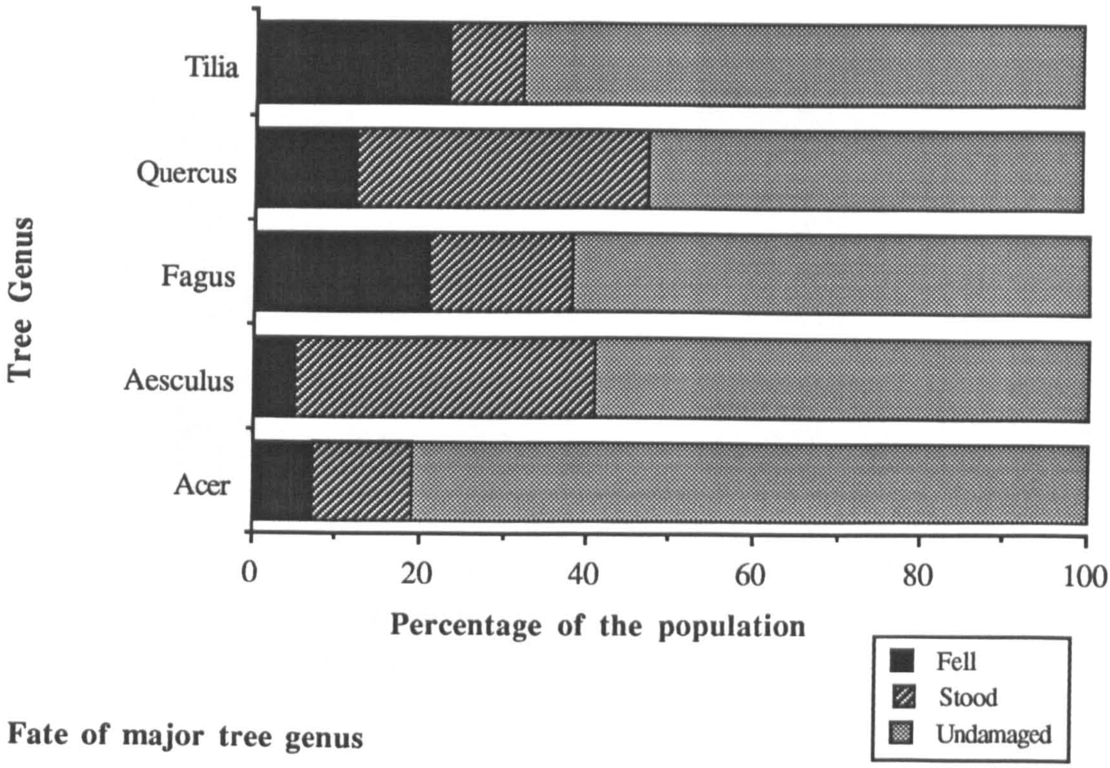
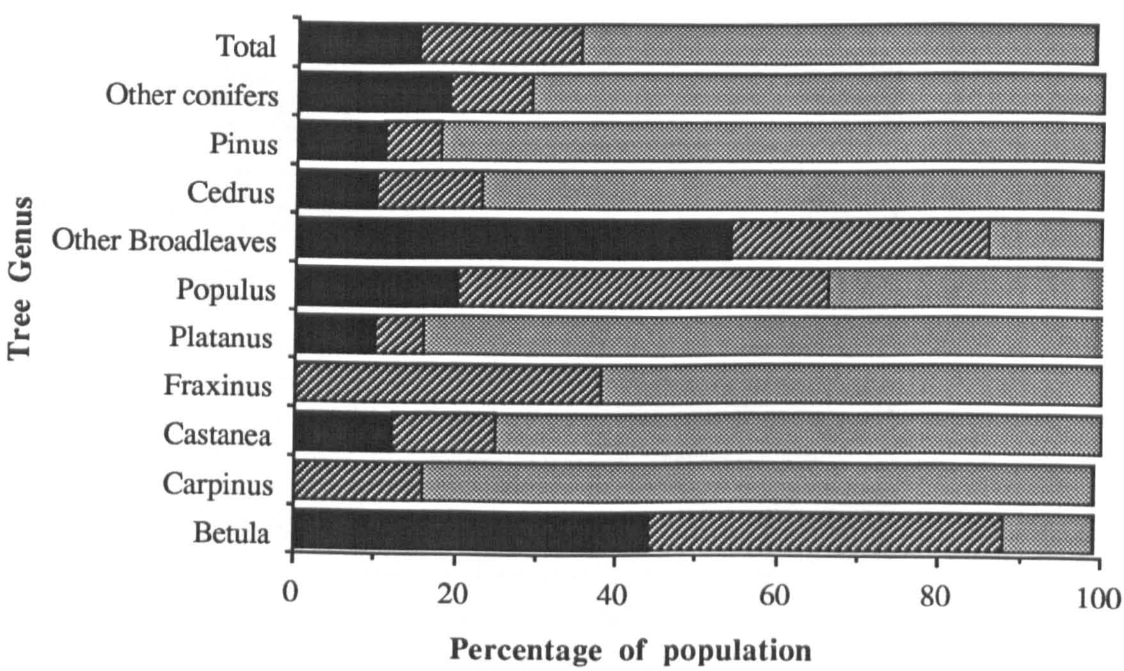


Figure 3.7 Kew trees - fallen

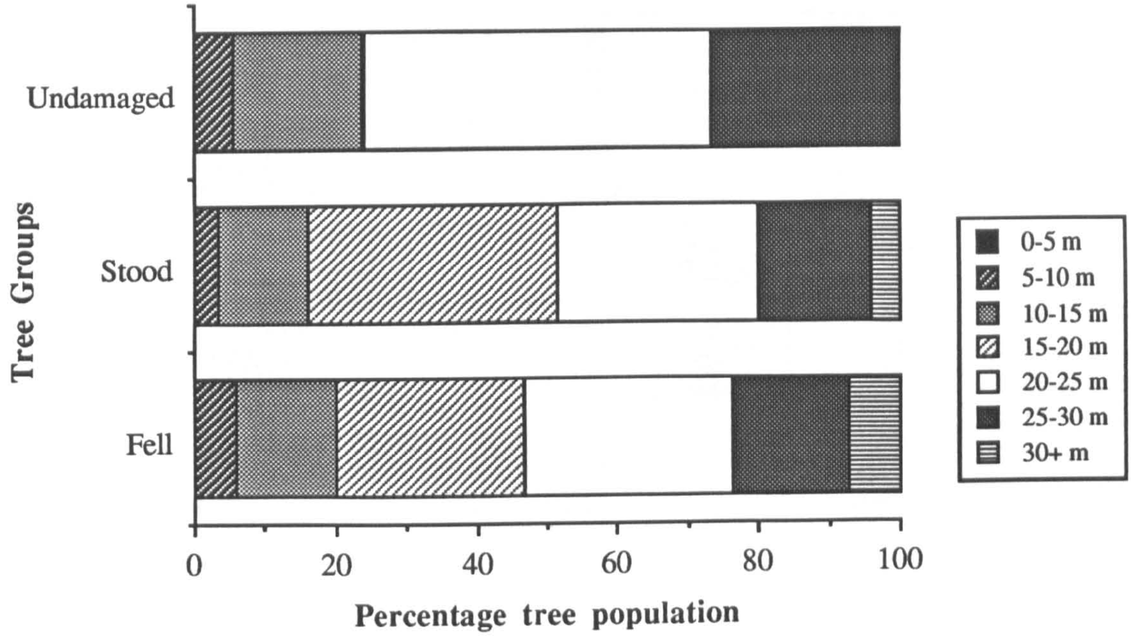


a) Fate of major tree genus

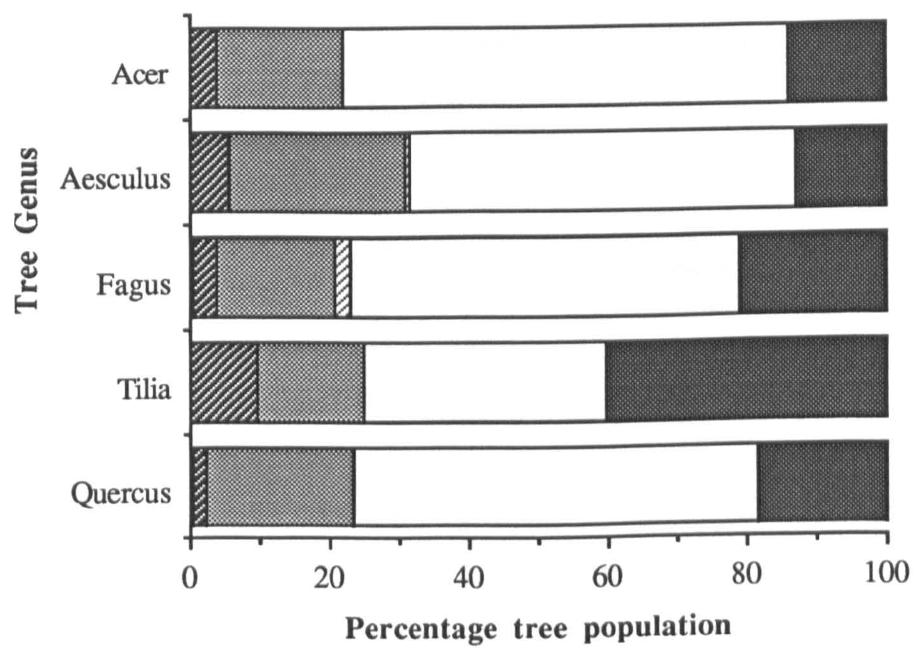


b) Fate of minor tree genus

Figure 3.8 Fate of selected F.C. tree genus

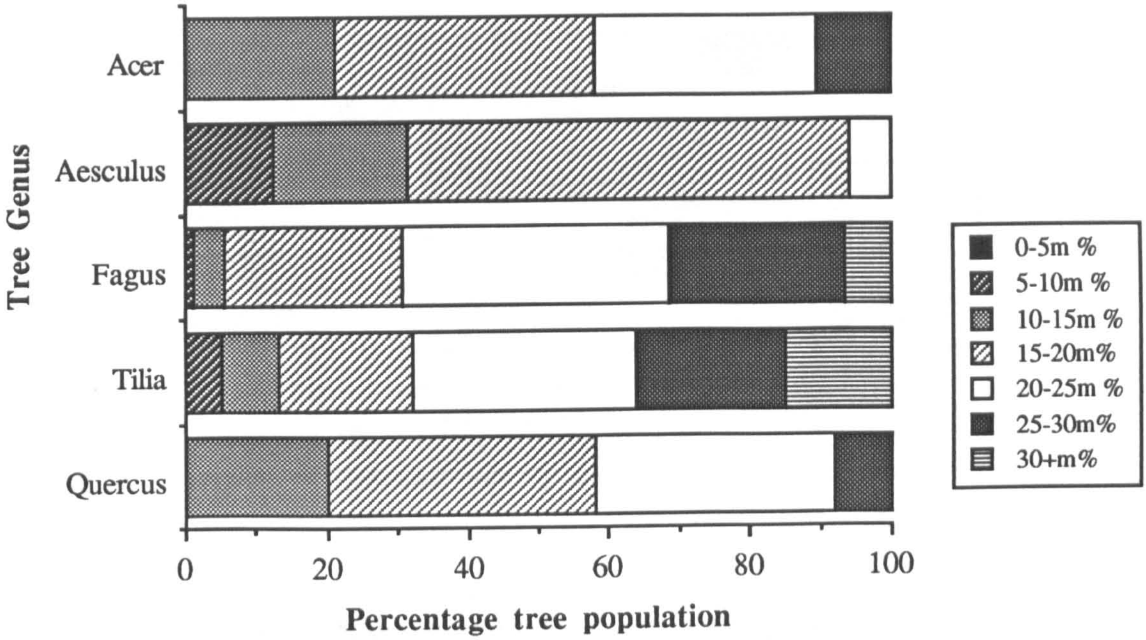


a) F.C. total tree population

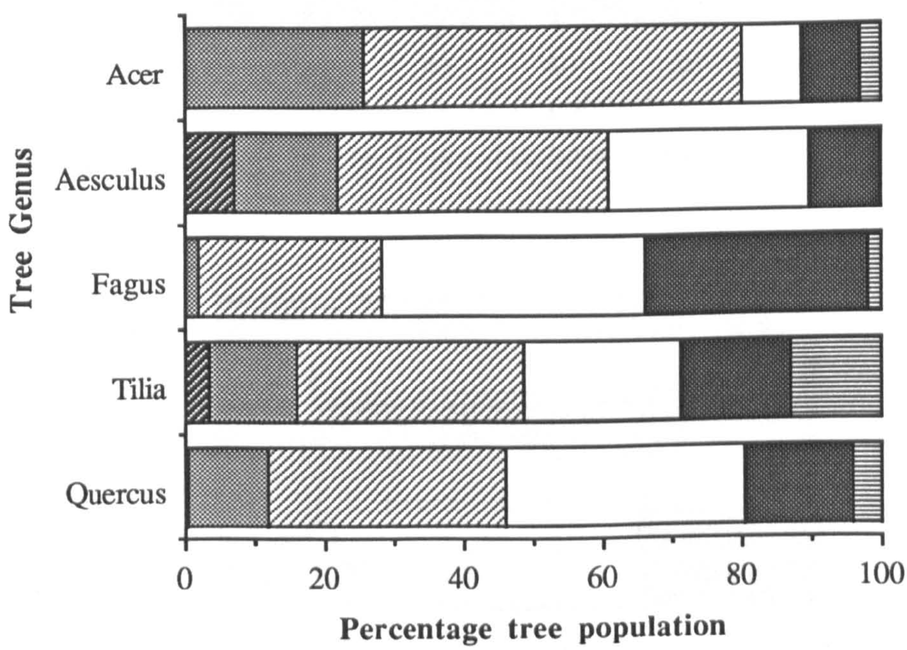


b) F.C. undamaged

Figure 3.9 Heights of F.C. trees for each fate group



c) F.C. fallen trees



d) F.C. trees which stood but were damaged

Figure 3.9 Heights of F.C. trees for each fate group

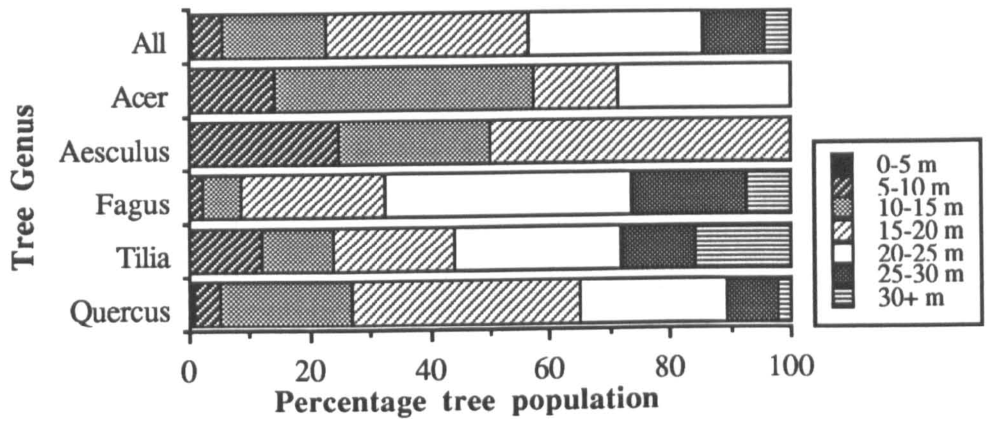


Figure 3.10 Heights of the Kew survey trees

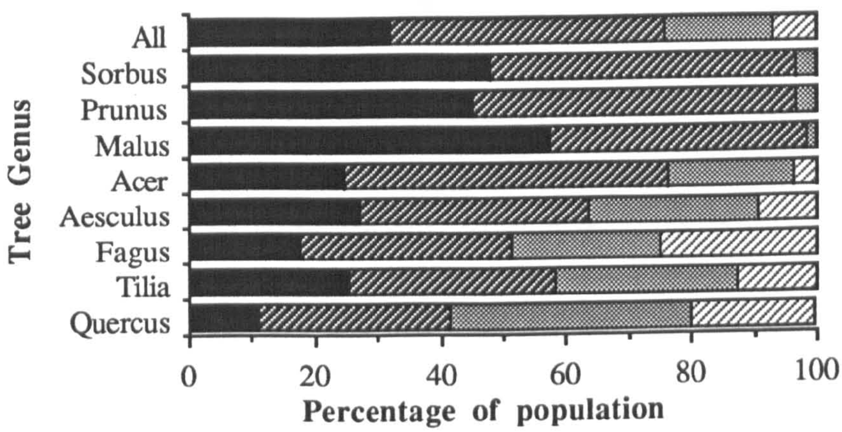


Figure 3.11 Heights of the Essex database trees

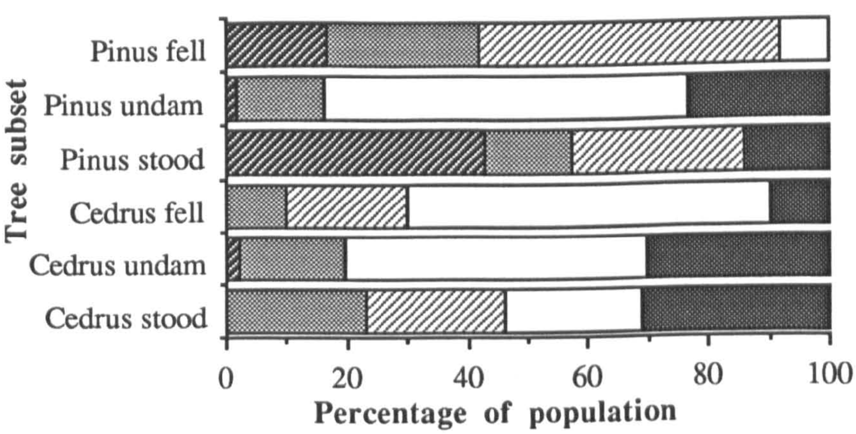


Figure 3.12 Heights of F.C. Pinus and Cedrus trees

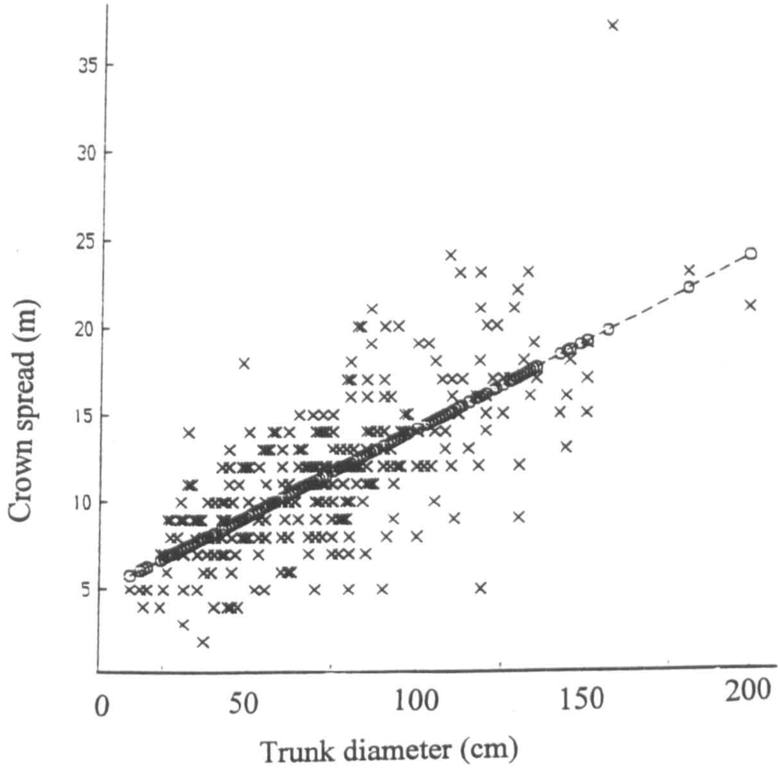


Figure 3.13 Crown spread versus trunk diameter

F.C. fallen trees

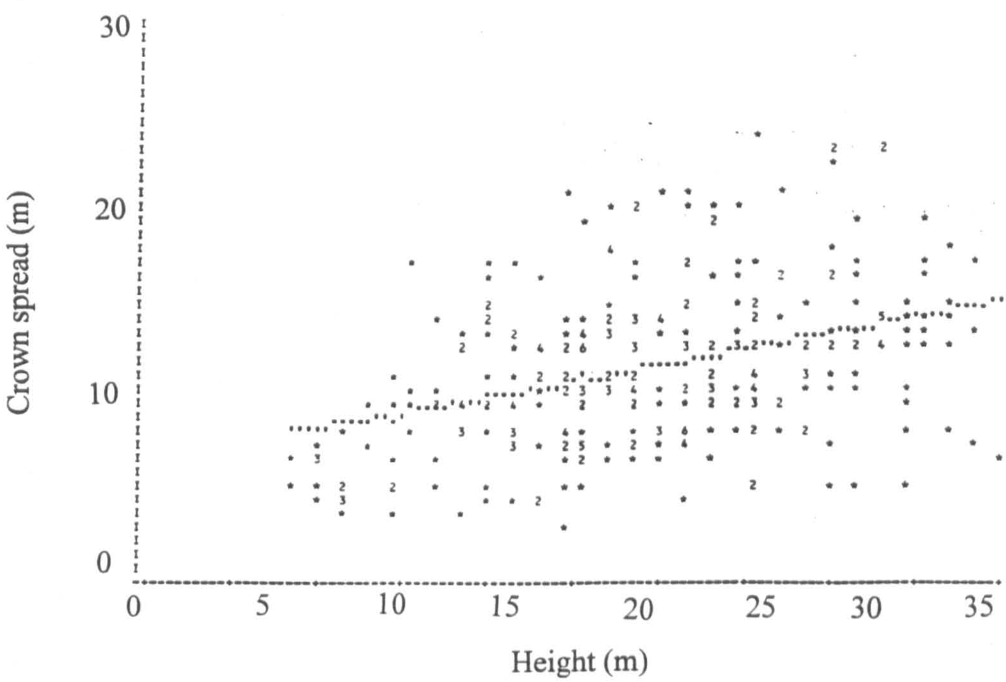


Figure 3.14 Crown spread versus height

F.C. fallen trees

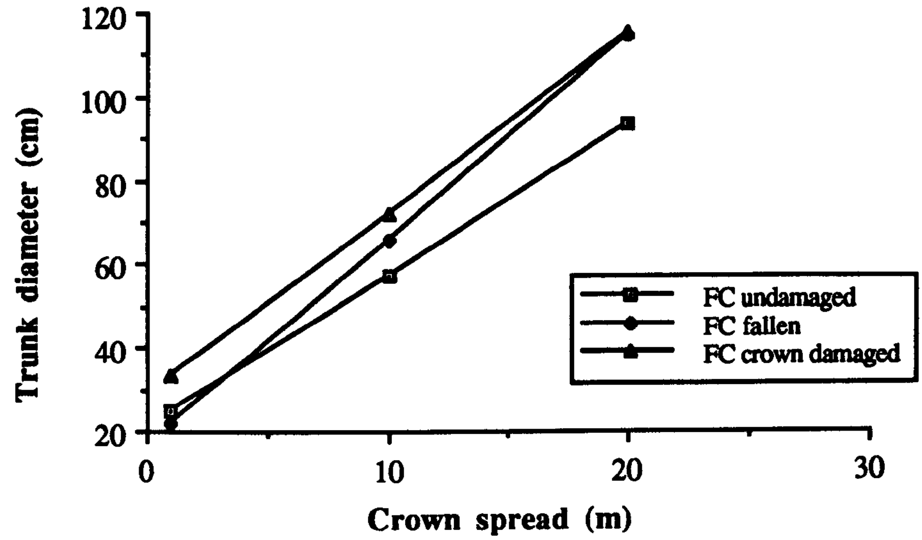


Figure 3.15 F.C. trees
Regression lines of trunk diameter versus crown spread

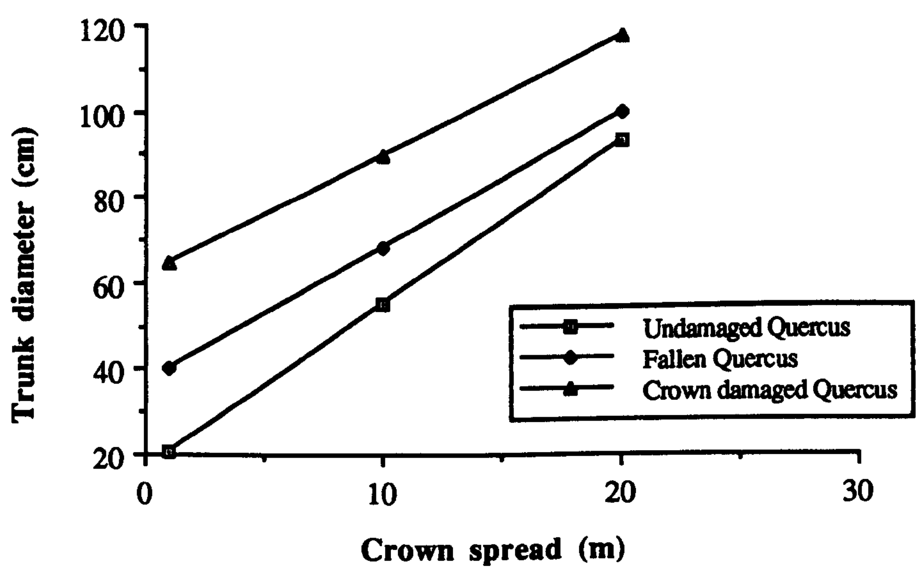


Figure 3.16 F.C. Quercus
Regression lines of trunk diamater versus crown spread

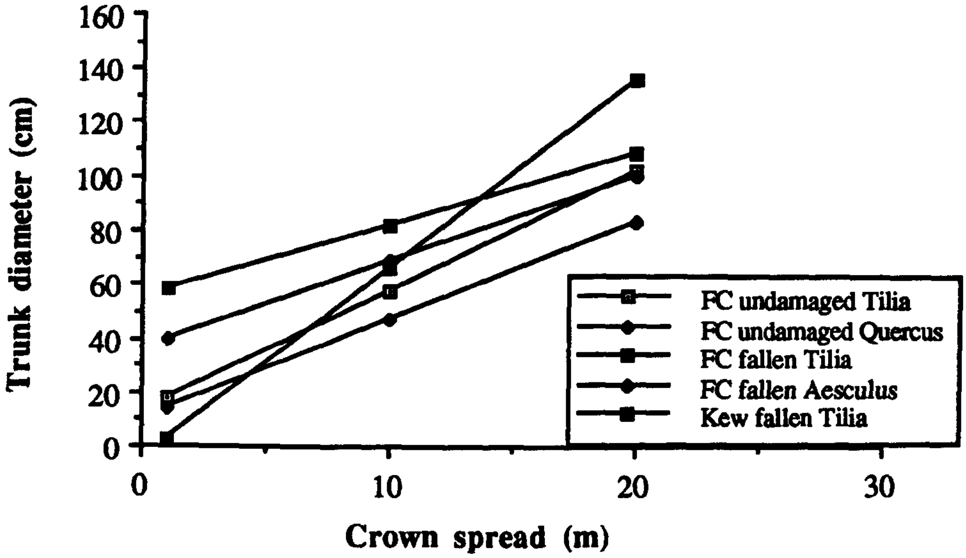
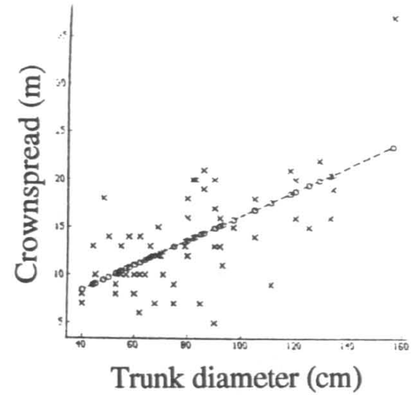
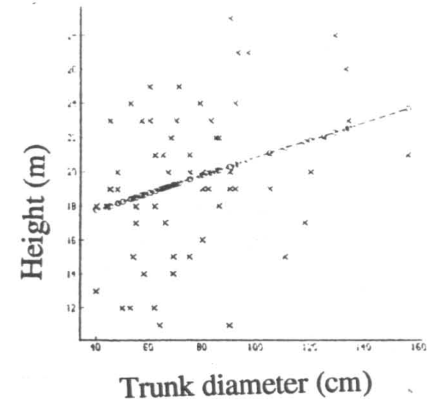


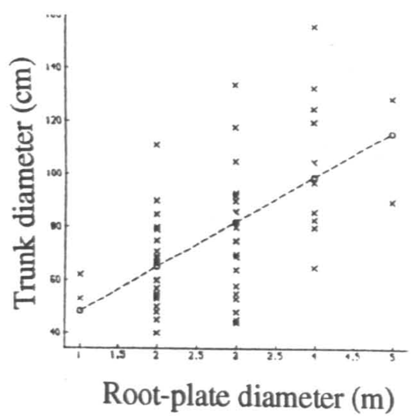
Figure 3.17 **F.C. fallen Tilia**
Regression of trunk diameter versus crown spread



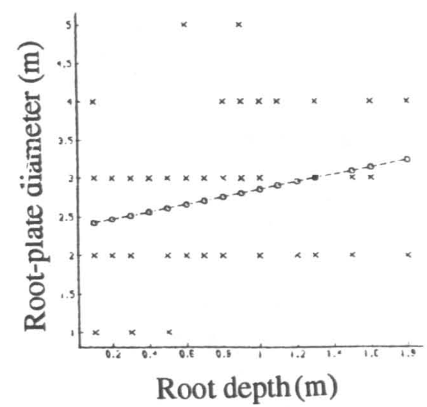
a Crown spread versus trunk diameter



b Height versus trunk diameter



c Trunk diameter versus root-plate diameter



d Root-plate diameter versus root depth

Figure 3.18 **Series of regressions for aerial and subterranean parameters of F.C. fallen *Quercus***

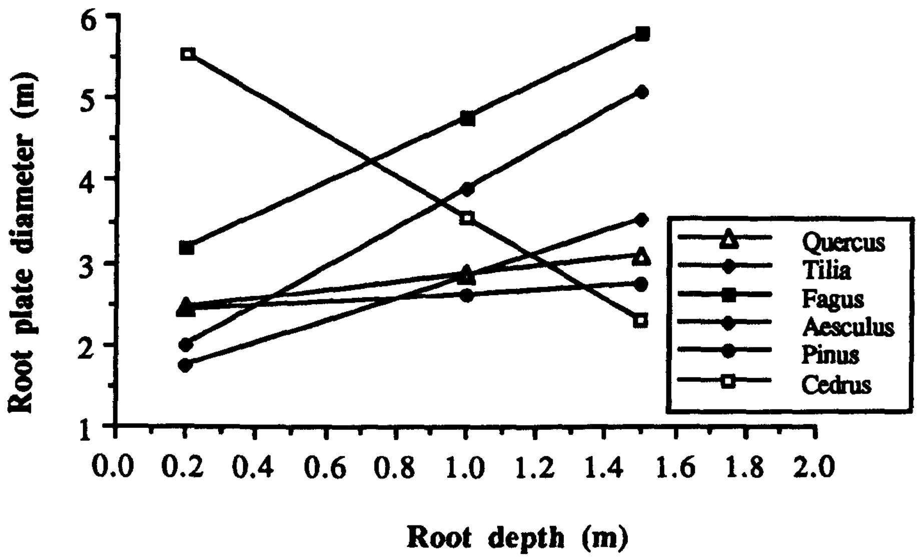


Figure 3.19 F.C. trees
Regression lines of root-plate diameter versus root depth

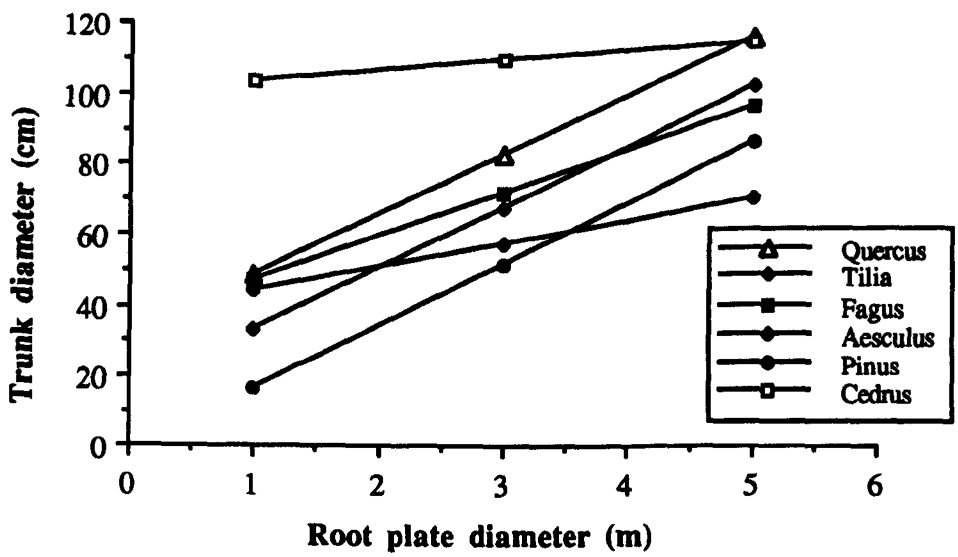


Figure 3.20 F.C. trees
Regression lines of trunk diameter versus root-plate diameter

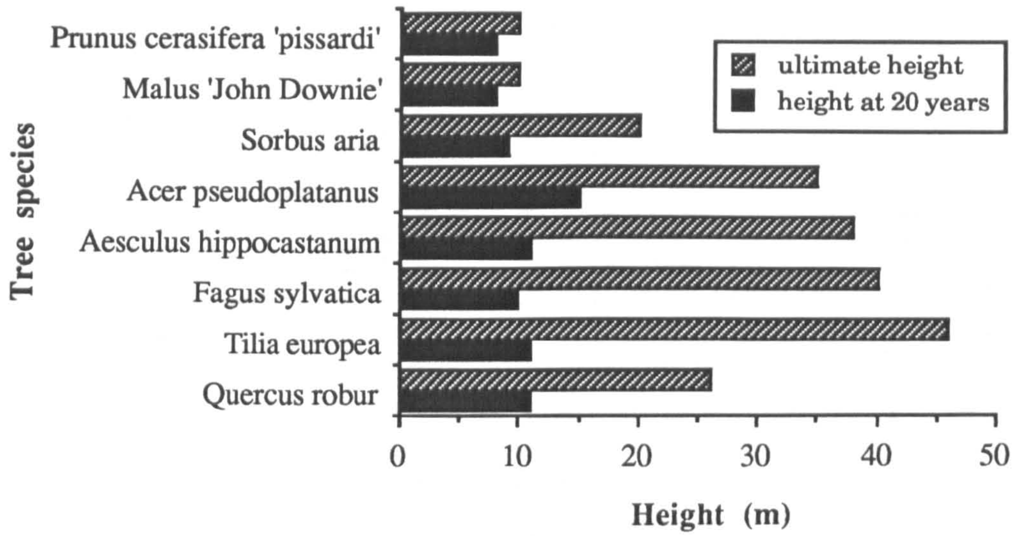


Figure 3.21 Ultimate and 20 year old heights of popular tree species (Mitchell and Wilkinson 1989)

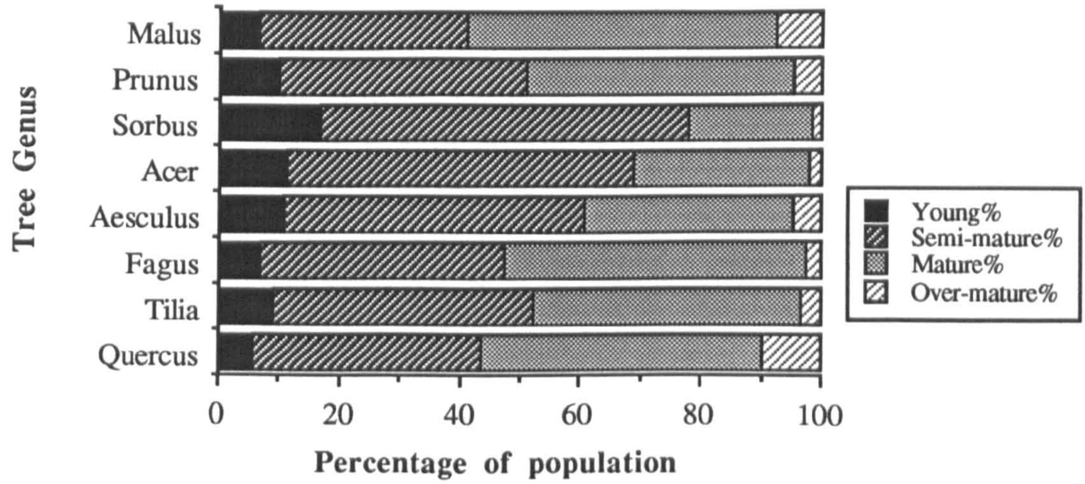


Figure 3.22 Age distribution of Essex database trees

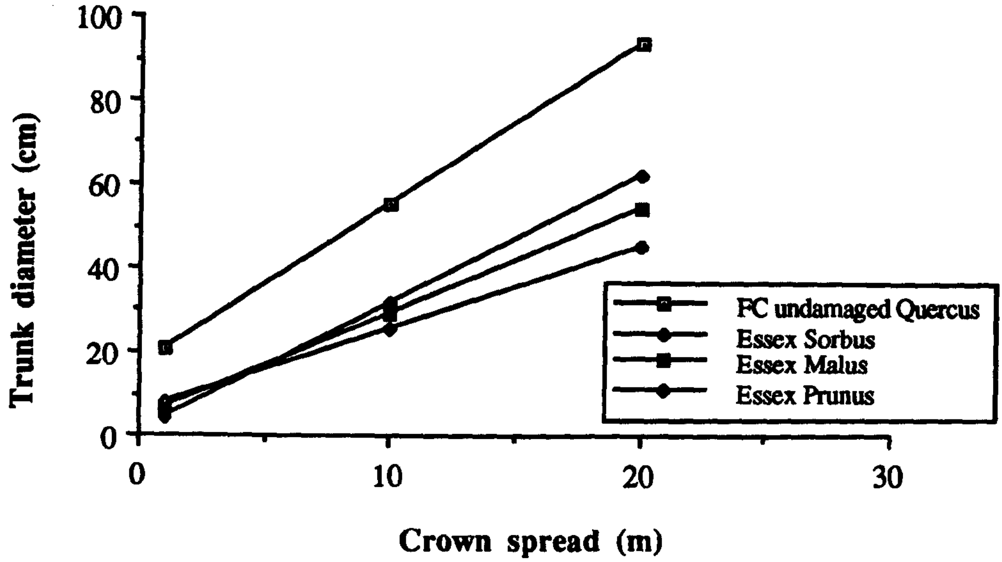


Figure 3.23 Essex Malus, Prunus and Sorbus
F.C. Quercus
Regression lines of trunk diameter versus crown spread

Chapter 4

Site Visits

4.0 Introduction

During the period of the research at Nottingham, three major storms occurred. These storms gave the author an opportunity to observe the damage strong winds can cause to trees. The storms occurred as follows:-

a) in Scotland on the 13th/ 14th February 1989,

b) on the Welsh coast on the 14th August 1989,

c) in the south of England and Wales on the 25th January 1990.

Site visits were made to Aberdeen in February 1989, and to Llanhydroch Park in Cornwall, Killerton Park in Devon and Saltram House in Devon in January 1990. Visits were not made to the Welsh coast following the August 1989 storm, as little tree damage was reported, most likely due to the sparse tree population in that area. Observations of tree fall were also made within Derbyshire and Nottinghamshire following strong winds during the winters of 1989 and 1990.

The objectives of the site visits were :-

a) To assess the problem of tree damage by high winds in general,

b) To raise questions and provoke ideas as to why particular trees fall and not others, and

c) To investigate the mechanics of tree failure.

On a more practical level, these objectives were to involve:-

i) the observation of types of tree failure,

ii) the collection of tree species data,

iii) the collection of tree location data,

iv) the collection of tree mensuration data.

Surveys carried out on these site investigations also provided experience of survey techniques and data collection. It was hoped that this would assist the author in the interpretation and assessment of the results of similar surveys conducted by other bodies (the Forestry Commission and Kew, Chapter 3).

Details of the surveyed sites follow in Section 4.1. Each site is described in terms of location and type, with the dominating tree genera stated. Wind speeds recorded at the nearest meteorological stations are given. The mean wind speed is the mean of wind speeds recorded in the 10 minutes preceding the hour, and gust speeds correspond to 3 second gusts. The general soil type is also given for each site, though the individual tree records (Appendix B) may show this to vary slightly within the site.

The methods used in the data collection are given in Section 4.2.1. Limitations of these methods, and to the survey in general are then discussed (Section 4.2.2).

Observations are made which are illustrated using photographic records (Section 4.3). These include details of the tree species (Section 4.3.1), the type of failure (Section 4.3.2), root-plate descriptions (Section 4.3.3), instances of inhibited root growth (Section 4.3.4), and the effect tree location has on tree stability (Section 4.3.5). These observations are followed by a numerical analysis of the data (Section 4.4). Where possible, the procedures used are the same as those employed to evaluate the F.C., Kew and Essex data (Section 3.2), though the size of the data sets is considerably smaller.

Comparisons are then drawn between the author's survey and those conducted by the F.C. and Kew (Section 4.5). This is followed by the conclusions drawn from the site visits (Section 4.6).

Section 4.7 effectively concludes both Chapters 3 and 4 in a discussion of survey techniques, their values and associated problems. This draws not only on the experience of the author and the site visits to Aberdeen and SW England, but also to points raised and problems encountered during the analysis of the F.C., Kew and Essex data.

4.1 The Sites

The location of the sites visited and the nearest Meteorological Stations from which data was obtained are shown on Figure 4.1.

4.1.1 Aberdeen

Despite being in an urban environment, the surveyed trees are not specifically street trees, many growing in parks and 'green open spaces', and only a few growing close to a road or path. The majority of the trees surveyed are in Seaton Park (GR. 37408090). The tree population is dominated by *Fagus* and *Ulmus* (Elm) and these genera are therefore the principle subjects of observations. One *Tilia* was also studied.

Wind speeds of 15.9 $ms^{-1}$with maximum gusts of 37.6 ms^{-1} were recorded on 13th February 1989 at Peterhead Harbour, and at Dyce wind speeds reached 22.6 ms^{-1} with 37.0 ms^{-1} gusts. These are the nearest meteorological stations to the city.

The surrounding ground is dominated by mown grass, though a more diverse flora is observed around some trees. Trees are located on land that is flat or gently sloping. Trees in obviously exposed positions e.g. cliff edges, hill tops, or on steep slopes are not included in the survey.

The soil type ranges from clay though loam to sand. Moisture contents of 25±5% on clay and loams, and 12±4% on the drier sandy sites were measured two days after uprooting.

4.1.2 Llanhydroch Park (GR. 20900636)

This site suffered substantial damage in February 1990. The tree population here is dominated by *Fagus*, with *Quercus* as the second most represented species. The main parkland area, includes a double avenue of *Fagus* which is sheltered by a hill wooded largely with *Fagus*. The wind appears to have come from behind this hill during the 1990 storm. Much damage has occurred to the shelter-belt trees but many of the specimen park land trees remain intact. The parkland is predominantly flat with very gentle slopes.

Winds of 26.7 ms^{-1} were recorded at Chivenor with maximum gusts of up to 41.2 ms^{-1} on 25^{th} January 1990, though it should be noted that Chivenor was on the North coast of Devon and not inland like Llanhydroch.

Soil descriptions within the site include:- yellow/ brown lightly weathered shale/ very gravelly clay; green brown, slightly organic, very silty clay with gravel sized shale fragments; and clay with angular laminated shale. Soil moisture contents were not taken for this or any other site in Devon or Cornwall as the sites were not visited until approximately a week after the storm. During this interlude evaporation, drainage and rainfall may have substantially altered the soil moisture status.

4.1.3 Killerton Park (GR. 29730998)

The parkland of Killerton House in Devon is an open pasture land with trees generally growing singly or within widely spaced groups. The land is fairly flat with the wind fetch being across gently undulating land. The tree population is dominated by *Quercus* though this includes not only the *Quercus robur*, but *Quercus X hispanica* 'Lucombeana' (Lucombe Oak, a Hybrid species generally only found growing south west of Bristol), and *Quercus ilex* (Holm Oak). *Fagus* is also present on the site. Examples of all these genera are seen uprooted while other specimens of the same species remain standing.

Wind records from Exeter show that wind speeds of 22.1 ms^{-1} occurred on 25^{th} January 1990, with maximum gusts of 38.1 ms^{-1}.

The soil type varies only slightly over the site, from a red/ brown, soft/ firm very clayey silt with occasional pockets of sand to a brick red, silty clay.

4.1.4 Saltram House (GR. 25160555)

In the south of Devon, Saltram House suffered storm damage in the winds early in 1990. The grounds outside the immediate gardens of the house are pasture land, though of a less formal layout than Killerton. The land is more uneven, though it still could not be described as hilly. Trees were observed to fall on both sloping and flat ground, and a *Pinus* was uprooted on the top of a ridge on the woodland boundary. The tree population includes *Quercus X hispanica* 'Lucombeana' - *Tilia*, *Acer platanoides* and *Pinus*. The *Acer platanoides*, not a native species, indicates that at least some of the trees were planted as part of the estate, and are not just remaining specimens from cleared woodlands.

This site was exposed to winds of 30.9 ms^{-1} during 25^{th} January 1990 with maximum gusts of 43.2 ms^{-1}. These wind speeds were recorded at Mount Batten, the nearest meteorological station to Saltram.

The soil is generally poor agricultural soil, a thin layer of which overlaid a shale at various stages of weathering.

4.2 Data Collection

4.2.1 The survey procedure

At each site general observations were made and noted in the site descriptions (Section 4.1). The trees were then inspected in a methodical order with the species and location being noted first. Measurements were then made of the aerial and subterranean dimensions where possible. The heights of the standing trees were measured with an inclinometer. A tape measure was used for the fallen trees. Photographs were taken of most trees from various angles with close-ups of the root-plates. A selection of these photographs are presented in Section 4.3.

The data was recorded on survey sheets, with details of the trees' immediate environment. The survey sheet for the south of England is given (Fig. 4.2) with definitions and explanations of the qualifying parameters where necessary.

Missing values are expected as in the F.C. survey (Section 3.2.1).

4.2.2 Limitations

Time limitations restricted the number of trees which could be observed. Initially, on the Aberdeen survey, it was decided to restrict observations to fallen trees and collect the maximum data on the entire tree, that is, including the root system, and associated wind and soil conditions. On later surveys it was decided that comparisons should be made with standing trees and a small number were recorded, though only their aerial parameters could be measured. The later survey sheets were also developed to include greater quantitative detail on the aerial tree parameters and rooting structure. This included, for example, detail of the crown, and length of clear trunk below the crown, root thickness at the snapping point, and the depth of soil above the roots. The qualitative information which includes the nature of the surrounding ground cover, the presence of asymmetrical growth and crown unevenness, and whether the tree has been pollarded or the subject of major crown reductions, was regarded with less importance and grouped in 'other comments'.

The trees observed were not scientifically nor randomly chosen by species or location. The observations were dictated by the wind and the tree population prior to the storm. The size, species and specimens does not, therefore, conform to a controlled experiment, making the results more complicated to interpret and the analysis less statistically reliable. Time limitations did not allow all the trees on a particular site to be surveyed. There was perhaps therefore a bias towards the investigation of the unusual. This was done at the expense of the loss of some repetitive data which would perhaps have helped to indicate the likely frequency of any one particular fate or in any particular species.

Meteorological data for each site was vague. Data from the nearest meteorological station could give only a general picture of the area, not specific to each tree. Each tree would have been subjected to wind conditions which varied due to specific location, aspect, upwind surface roughness and the obstruction and interaction of wind with neighbouring structures.

The research project is concerned primarily with the isolated broadleaf tree growing in urban/ roadside locations, though a small number of conifers were also measured to provide some comparison with the broadleaf trees. Problems were encountered in the surveying of fallen trees at urban and roadside locations, as they were rapidly cleared before surveying commenced. Park lands could provide isolated trees and they may also simplify the situation in so much as the roots are likely to be subjected to fewer man-made restrictions. Airflow patterns were also expected to be simpler in the park lands due to lower surface roughness values, and the general absence of surrounding buildings.

4.3 Observations

Full descriptions of each tree, as recorded on the survey sheets, are given in Appendix B. Selected observations are reported first with the aid of photographs and then a statistical summary of the numerical data is given. The results are then compared with those of the F.C. and Kew (Chapter 3).

4.3.1 Tree genera population

Fagus and *Quercus* were the most numerous genera found in both the fallen and standing categories. Fallen *Tilia* and *Ulmus* were the next most frequent, with one fallen *Acer* and one fallen *Pinus* also recorded (Figs. 4.3, 4.4).

4.3.2 Type of failure

Tree failure was observed in various forms; uprooting, branch breakage, and trunk breakage (Plates 4.1, 4.2, 4.3). One *Aesculus* failed at the base of the tree, neither the roots nor the trunk, were broken, but it appeared that the trunk had been rotated and fractured at the trunk/ root interface (Plate 4.4). A number of trees were also seen to be only partially uprooted (Plate 4.5). Measurements were made of a number of parameters for the partially uprooted trees, as it was thought that this may be important in the analysis of uprooting. Figure 4.5 shows these parameters, including the vertical ground displacements on both sides of the trunk, and the distances at which they occur. Table 4.1 presents the values of these parameters for a number of specimens.

Trees growing singly (Plate 4.6) and those in groups (Plates 4.7, 4.8) were both seen to fail. It was noted that on each site some trees of a particular species fell, whilst others of the same species stood undamaged. An example of this was seen at Killerton Park. A *Quercus ilex* fell (Plate 4.9), whilst a second, (shown in the background of Plate 4.1) stood undamaged.

Though few young trees were recorded in the survey, they are still vulnerable to strong winds. Plate 4.10 shows a wind damaged young *Fagus*.

Rot, disease and decay were present in a number of trees particularly those in Aberdeen. The decay was seen to affect the tree roots, (Plates 4.11 and 4.12) and the base and trunk of the tree, (Plates 4.13 and 4.14 respectively). The majority of the trees which snapped at a part in the trunk or base were observed to be host to decay.

4.3.3 Root-plates

Roots have been reported to spread great distances from the tree trunk, certainly beyond the drip line of the trees' canopy (Helliwell 1986). The full extent of the root system however was not researched in this survey. It was decided that the benefits gained from such a course of action would not justify the time required to do so. The visible root-plate was considered to be of paramount importance when considering the structural stability of the tree. (This does not imply however that without the outlying root system the tree would thrive or even remain upright.)

The root-plates were generally of the form of lateral roots radiating from the base of the trunk. These laterals were seen to taper dramatically even within 1 or 2 metres of the trunk, to diameters of perhaps only 5 or 6 centimetres. The root-plate radius appeared surprisingly small in comparison with the trees' trunk diameter and height. An extreme example of this was illustrated by the large *Fagus* (Plate 4.17), with a root-plate radius of 1.5 m having a trunk diameter of 1.2 m (measured at 1 m from the ground), and a height of 18 m. Root-plate diameters of up to 6 m were measured, but the mean of all the surveyed trees was 3.8 m. Root-plates were also found to be shallow, usually only one metre deep or less. In all the surveys the maximum depth measured was 2 m, with a mean value of 0.8 m.

These observations confirm the ideas detailed in the literature review (Section 2.4.1), concerning the 'tap' root, or rather the lack of a major tap root. The root system was observed not to reflect the aerial part of the tree, in particular the depth of root into the ground did not equal the height of the tree. No significant tap roots were observed in any of the mature trees surveyed. Tap roots were located in some root-plates however, but they were only present as rotten remains. Their relatively small diameter (3 cm), indicates that the tap root must have fulfilled its purpose in the early years of the trees life. Once the tree becomes established, it appears that the tap root is superseded by the horizontally spreading lateral roots, and the tap root is no longer useful to the tree. The location and size of the initial tap root is demonstrated by a *Fagus* in Plates 4.19 and 4.20. Similar observations were made of a *Quercus* (Plate 4.21).

A number of trees did not have the laterally spreading root pattern. A young *Quercus* (Plate 4.1) had roots which enter the soil at a greater angle and were therefore not true laterals - though not dropping vertically either. A second young *Quercus*, (Plate 4.18) has a multiple tap root which comprised of a number of thin roots 3-4 cm in diameter, twisted together, and dropping vertically below the trunk.

The form of tree roots was also seen to vary between species. In particular it was noted that *Ulmus* had many more fibrous roots than the *Fagus*. (Incidentally this does reflect trends in the aerial structure of the species.) The importance of this in structural terms however, was not obvious. The root-plate radii and depths recorded for the two species in Aberdeen (as this was the only place *Ulmus* were observed) showed no particular variation in size.

Trees with root lift, but not total uprooting were observed (tree nos. 16, 19 and 21). These may provide useful information concerning tree stability. Soil level profiles were made of these trees (Fig. 4.5, Table 4.1). However it was felt that further work is required in the mechanics of uprooting before conclusions can be drawn from the data.

4.3.4 Inhibited growth

A number of trees were observed to have their root growth restricted. Restrictions were seen to be caused by environmentally influences, both naturally occurring and man-made.

At Saltram House the soil was very shallow overlying virtually impenetrable shale. The rooting systems here were found to be exceptionally shallow, usually less than 40 cm deep, with only a few thin, flattened roots extending downwards. These vertical roots grew directly below the trunk of many trees, along fissures in the shaly sub-soil, and even then extended to a depth of no more than one metre.

Root-plates also tended to be shallower on wetter ground. The roots of an *Ulmus* in Aberdeen extended only to a depth of 0.5 m. The uprooting process had not broken any roots, merely lifted them from the soil. At the time of surveying (two days after the storm which caused the uprooting), this particular area was waterlogged.

A large *Fagus*, (Plate 4.22) had its root spread hampered by a deep drainage ditch on one side. Root growth tends to be directed for nutrient and water uptake. This requires them to be in the upper soil layers which are nutrient rich, and not waterlogged. Root growth would have been prevented beneath the ditch, as the depth of the ditch was greater than the depth of to which roots tend to grow. Also there would be a great likelihood of water logging at least during the winter months. If the tree was present before the ditch was excavated, the roots were probably severed in the process.

An *Ulmus*, (Plate 4.23) had possibly suffered compaction on two sides of the root-plate, during the making of an impervious, bituminous footpath. The tree roots did not penetrate directly below the path. This was perhaps due to the physical compaction or due to the reduction of the rate of water infiltration in the volume of soil below the path. The great depth of the root-plate suggested that the footpath was constructed around the established tree, and in so doing the ground level raised around the tree. As a consequence all the lower roots were seen to have died back.

4.3.5 The effect of tree location

The question of why certain trees fall and not others is not clear, but it cannot be dependent solely on the tree's physical parameters, as apparently similar trees were seen to suffer different fates. Their stability may also depend upon surrounding conditions.

Two *Fagus* trees within a group of 8 *Fagus* at Llanhydroch Park had fallen (Plate 4.7). It appeared that all the trees had similar aerial structures, and the root-plates of the fallen trees were apparently healthy. It was noted, however, that the fallen *Fagus* were on the windward edge of the group and were perhaps less sheltered by the *Fagus* avenue. The fallen trees therefore possibly intercepted more wind. It may be simply that the storm abated before further damage occurred. Another plausible reason for those two trees falling is perhaps the root-plates were not as large as their neighbours. This will remain unknown as the trees could not be sacrificed for this research.

The large *Fagus* (Plate 4.17) was by far the largest tree on the hillside at Seaton Park and its crown would have protruded above the general canopy. This perhaps explains why it was the only tree on the hillside to fall.

Of the Aberdeen trees it was noted that many trees (specimens 1, 2, 7, 10, 14, 18, 19, Appendix B) were the first large structures encountered by the wind after crossing an area of open land. However many of these fallen trees had neighbours, which were seemingly undamaged by the wind, suggesting that it is not the wind interception alone which is responsible for the uprooting of the tree.

The shelter aspect cannot be used to explain the failure of the two *Populus* in the line at Highfields Park, Nottingham (Plate 4.8). The entire line of *Populus* were sheltered by a row of *Tilia*, though not to their extreme height, but the two that snapped were visibly no more exposed than the others.

The *Fagus* (Plate 4.4) which fell across the road in Aberdeen, though suffering from some root rot, may have been made more vulnerable by the presence and arrangement of houses situated close by. The rows of houses were aligned with the wind direction and may have caused a channelling effect of the wind.

4.4 Numerical analysis of the data

Numerical data was extracted from the surveys sheets and statistical analysis carried out in order to quantify the results. This analysis was limited by the relatively small number of trees surveyed (37 fallen, 6 standing) particularly when comparisons were drawn between genera.

Details of the measured tree parameters are given in Tables 4.2 and 4.3 for the fallen and standing trees respectively.

Tree heights were observed to vary between 5 m and 26 m with the majority between 10 m and 20 m for the fallen trees (Fig. 4.6), and 20 m - 25 m for the trees still standing (Fig. 4.7).

Regression lines were calculated for trunk diameter versus tree height, trunk diameter versus crown spread, trunk diameter versus root-plate spread, and root-plate spread versus root depth, for both the fallen and standing trees, and also for the fallen *Fagus* and fallen *Quercus*. T-tests were then carried out to compare selected sets of data. The values for the regression lines, with the percentage variance accounted for are presented with the T- test values in Appendix A.

No significant differences were found at the confidence level of 95%, between the fallen and standing trees, or between the major genera *Quercus* and *Fagus* in any of the above correlations, with one exception. The trunk diameter and root-plate spread of the *Quercus* showed a significant difference from both the *Fagus* and the entire data set. It appeared that the *Quercus* had root-plates which increased in diameter only with large increases in trunk diameter (Fig. 4.8). This is based on only 10 specimens. The root-plate dimensions were also taken to the nearest whole metre for ease in computation. This may have significantly distorted the data.

The data set was then split and the regression lines drawn for the trees growing in Aberdeen, and those not growing in Aberdeen. The purpose of splitting the data set in this way was to investigate whether the trees growing in Aberdeen are stunted since in response to frequent strong winds, trees are believed to form growth to counteract movement (Section 2.3). This would take the form of stem thickening, as this increases the bending strength of the tree. Although tree height alone cannot show this condition, the height/ diameter ratio may indicate it. The regression lines drawn for the parameters of tree height and, crown spread against trunk diameter showed little difference between the trees growing in Aberdeen and those growing in the SW England (Figs. 4.9 and 4.10). The t-tests confirmed this lack of significant difference at a confidence level of 95%

These statistics give an indication of trends of tree parameters, but it must be noted that the sample is very small, limited to few species of a small age range, and most analysis refers only of those trees which fell over.

4.5 Comparisons with F.C. and Kew results

4.5.1 Tree species

Comparisons made of the site visits with the F.C. and Kew surveys,, revealed similar species composition. Although the site visits had very limited numbers, the most popular genera (*Fagus*, *Quercus*), were those which feature heavily in the larger surveys. Additionally there was a relatively high proportion of *Ulmus*. The lower percentage of *Ulmus* in the F.C. and Kew surveys could be accounted for by the action of Dutch Elm Disease, which has virtually eradicated the species from England, particularly the South. Aberdeen, in the north of Scotland, however has not yet been devastated by the disease.

4.5.2 Type of failure

Tree failure was observed in all the differing forms as described in the larger surveys. No comments however, can be added on the relative frequency of each form due to the small number of entries. It was noted however that few young trees were observed either to be damaged or remain undamaged. Reasons for this are in the survey type and site selection, similar to those in the F.C. survey (Section 3.4.2). Attempts to explain each tree's fate in terms of location, presence of rot or abnormalities, were carried out. This was possible because there were only a small number of trees involved. However caution must be used, due to the small sample size.

Rot and disease did appear to be a major weakness in the trees, contributing to the failure of the tree. The frequency of decay was particularly high in Aberdeen, where 42% of the trees surveyed showed decay. This was greater than that found by the F.C. in their survey (Gibbs and Greig 1990), where 32% of the damaged trees had substantial decay present. In the SW England decay was present in 9% of those trees surveyed.

4.5.3 Root-plates

Recorded values of the root-plate radii lie within the ranges of those recorded by F.C. and Kew. The conclusions regarding the tap root is also in agreement. A further point of interest is the sloping roots of the young *Quercus* tree. *Quercus* with sloping roots were not uncommon in the Kew survey (Cutler, Gasson and Farmer 1990), but the ages of the trees were not noted. Their suggestion was that these roots became lateral at a deeper level. Cutler and Gasson (1990) also described a greater number of differences in the root form between species, unfortunately though only one *Ulmus* was present in their survey and so descriptions of its roots were omitted.

Partial root lift was noted by the F.C., however measurements of distances and displacements if made, were not reported, so comparisons cannot be made with the observations of the author.

4.5.4 Inhibited growth

The F.C. and Kew surveys did not allow for the consideration of inhibited root growth. The site visits suggested however, that inhibited root growth of whatever form, may be a significant factor in the trees instability, increasing the likelihood of failure. Inhibited root growth and root decay were generally observed on the windward side of the tree (though the lee side roots were sometimes buried). This supports the findings of Coutts (1986), which showed the windward roots to be of far greater importance in term of tree stability than the lee side hinge (Section 2.4.2). Were the tree to have lost the lee side roots but still maintained its windward roots the tree would have stood a greater chance of surviving the strong winds.

4.5.5 Numeric analysis of the trees parameters

The trees aerial parameters were in good agreement with those in the F.C. and Kew surveys.

Comparisons made with appropriately selected subsets of the F.C. data also reveal no significant differences between the regression lines of paired parameters, with only one exception. The regression of the trunk diameter versus root-plate spread for the F.C. fallen *Quercus*, was found to be different from genera in the same survey. Again it appeared that the *Quercus* had root-plates which increases in diameter only with large increases in trunk diameter (Fig. 4.8). This is based on only 10 specimens as opposed to the 61 *Quercus* in the F.C. data set.

4.6 Conclusions

The site visits achieved their purpose and made the author more aware of the casualties arising from storm damage. In considering only the small number of trees surveyed it has become clear that tree fall is very complex. The occurrence and type of damage inflicted on the tree is not dependent on one, two or even three factors, but is a combination of many factors. These may be both external environmental influences and features intrinsic to each individual tree.

From this small survey and observations in Nottinghamshire and Derbyshire it was observed that *Fagus* had a tendency to uproot (Plates 4.7, 4.16, 4.17). In contrast all the *Aesculus* and *Populus* surveyed were damaged by crown or stem breakage (Plates 4.4 and 4.8). However these results are far from conclusive because of the small number of trees observed.

Observations of the root-plates suggest that, generally, they are shallow, with lateral roots radiating from the trunk. This was seen in all the soil types, though perhaps the roots were a little shallower on the shale and thinner soils at Saltram House. The development of this rooting system remains a mystery. The sapling tree has a tap root which at some stage dies back and is replaced by these laterals. The young *Quercus* (Plate 4.1) with angled roots suggests that this could be a progressive transition, but many more observations are required of semi-mature trees before this could be confirmed.

The surveys show tree failure by different means and in different situations to a number of species. An attempt has been made to determine why particular trees fail and others do not. The answers, though perhaps plausible, do not give definitive reasons for each instance, they usually do not exclude the event of failure to the neighbouring undamaged tree, or the nearest tree of the same species. An example of this was posed by the *Quercus ilex* which fell in Killerton. Its uprooting could easily be explained, simply because they are evergreen trees, retaining leaves throughout the winter. More wind is intercepted by the dense foliage, and therefore a greater turning force causes uprooting. However, though this is a viable explanation, another *Quercus ilex* nearby withstood the storm. Although the species grows a large dense crown it is adapted to withstand high winds, by being compact, with only a short stocky trunk which effectively reduces the turning moment caused by incident wind forces. Also in being shorter, wind speeds can be expected to be less at the lower height.

Reasons suggested for tree failure include inhibited root growth, the location/ exposure of the tree and the presence of rot and decay.

Trees with root restrictions cannot establish laterals in all directions. Anchorage may therefore be less effective particularly if the windward roots are affected. The *Fagus* (Plate 4.22) was inhibited by the ditch on the windward side. Root restrictions were observed around the base of the *Ulmus* (Plate 4.23). The cause was either soil compaction, the lack of water infiltration, or possibly the combination of both these factors.

Tree failure may be due to structural failure of the tree itself or by failure at the root-soil interface. Structural failure occurs if the wind incident on the tree causes sufficient stress in the trunk to make it snap, before the turning moment at the ground exceeds that necessary to uproot the tree. The presence of decay weakens the inherent strength of the tree, so it is not surprising that it is often found at the point of trunk breakage. Decay in the rooting system also reduces the tree's stability, though it does not necessarily determine the direction of fall. Decay was observed both on the windward side of the tree, and at 90° to the wind direction. It could be that trees with root decay on the leeward side withstood the storm, suggesting that these roots are less important in stability. Alternatively the decay may have passed unnoticed if it were buried in the soil. As the uprooting process is currently thought to be a dynamic process caused by winds gusting and trees rocking it would seem that the leeward roots must be of some importance in stability, though not necessarily the major factor.

Generally, there was good correlation of both the author's visual observations and numeric findings with the F.C. and Kew surveys.

4.7 Surveys - a discussion of their value and their problems

4.7.1 Survey procedure

During the completion of the survey sheets, many ambiguities and oddities arose. It became clear that the design of the survey and the questions asked are very important. In this type of survey where the aim is to collect as much data as possible, there must be the option of extending the questionnaire - hence the 'other comments' section. The problem is that there is no sure way of knowing what data there is to collect and what will be important. However, on analysis of the data, qualitative and descriptive data is found to be of minimal use, and is seemingly only useful to qualify anomalies in the numeric data. This is likely to be increasingly so with larger numbers of samples.

From the author's experience in Aberdeen, alterations were made to the survey sheets to increase the amount of numerical data, and reduce the importance of the qualitative data. Even so, in the new situation, aspects arose which had not been prepared for (the leaning tree for example), and the need for flexibility in the survey became apparent. A seemingly sensible approach appears to be one in which each tree is examined and specific parameters, e.g. height, trunk diameter etc. are assiduously recorded, then descriptions and measurements are made specific to the tree in question. This does complicate the analysis but allows scope for individual attention. A balance is required. An alternative approach would be to increase the length of the survey, whenever a new situation arose, but this would lead to an inconveniently large survey sheet with most questions being either negative or irrelevant to the specimen under examination. To carry out such a survey might further limit the number of specimens which could be investigated.

4.7.2 Interpretation

A major problem of surveys is the interpretation of the question, particularly where the survey sheets are to be completed independently by different people or bodies. Definitions of the parameters under examination have been described within the method for the Aberdeen and the south of England surveys but there is still the problems of deciding where the root-plate ends, for example. With one surveyor it is likely that certain unwritten criteria are adopted and used repeatedly. With more than one surveyor, collaboration and comparison are advisable to minimise individual interpretation. It is almost inevitably that there will be some differences in the adoption of parameters criteria between the different surveys and perhaps even small differences in each survey. To minimise this each criteria must be carefully and clearly clarified.

A photographic record of the trees creates a visual image to support compiled survey information, and can clarify specific aspects. Photographs may resolve problems of ambiguity, particularly where the parameter value is descriptive and may be subjective of the assessor, the degree of crown density for example. Photographs may also portray specific details which are not easily described, for example the entire tree root-plate. The use of photography is however questionable and limited. The use of the photograph for deriving any numerical measurements is inadvisable. A ranging rod is present in many of the photographs, but even so the tree parameters cannot accurately be measured. The position of the rod is important, and really must be very close to, preferably touching the subject to stop errors caused by perspective. As the size of the survey increases, the practicalities involved in the photography and the filing and referencing of the photographs becomes very time consuming and of questionable value.

4.7.3 Problems of mensuration and analysis

Tree heights present a problem to the surveyors. Although equipped with even very sophisticated instruments, the actual apex could be concealed by the broader mid crown. This does perhaps suggest that the heights recorded for fallen trees are more accurate and reliable due to the relative ease of access to the information.

The vertical groupings displayed on the graph highlighted a mensuration problem, which is also seen in the F.C. and Kew data (Section 3.4.2). The tendency is to measure the root-plate diameter to the nearest half metre possibly due to the lack of clarity in the edges of the root-plate. This effect appears more prominent in the author's survey due to the small numbers of trees involved.

The grouping of points along the crown spread, trunk diameter and height axes of the F.C. undamaged data sets is due to the estimation of measurements to a number of preselected values. The values were selected presumably following preliminary analysis of the fallen and crown damaged data, to be used in comparison. The values chosen however appear arbitrary and not always even regularly spaced, greatly reducing the use of the data.

Soil descriptions are another area of discrepancy. The soil composition could be scientifically classified by collecting samples and running particle size analysis tests in the laboratory. This is very time consuming and its use in the role of assessing tree stability is not clear. Moisture content too could be experimentally determined, but its validity is in greater doubt due to the exposure of the soil in the time after uprooting, prior to collection.

A further limitation to the data was the resulting sizes of each data subgroup. Results, assumptions and trends were based on the comparisons of groups of greatly varying size. For example, a group of 12859 specimens (Essex school trees) was compared with 1293 (Essex 'other' site trees), 2491 (F.C. undamaged trees) with 272 (F.C. fallen trees), and 324 (undamaged *Aesculus*) with 8 (fallen *Aesculus*). The percentage variance accounted for was recorded, and generally lower for the smaller groups, however the comparison of greatly varying subset sizes is statistically not good practise.

4.7.4 Summary

In any survey the degree of accuracy gained should not outweigh the usefulness of the survey. However the validity of any survey is only as good as the information entered. The survey of Aberdeen and South West England were to generate ideas and experience storm damage very generally. Accuracy, though important, was not required in great detail as the surveys were exploratory.

The problem with the age of the *Sorbus*, described in Section 3.4.2 highlights problems encountered with this area of research, in that the researcher cannot prepare mature trees for observation or experimentation as the time scale required is not feasible. Instead conclusions must be drawn from specimens already available.

Greater accuracy would be useful in future, though even then the accuracy would not be that required of an experiment run in controlled conditions with specific numbers of repetitions and controlled variables.

These site visits helped to highlight the difficulties which are encountered during the survey procedure and enabled the author to assess the values of similar surveys with greater awareness.

Tables : Chapter 4

		Vertical root and ground displacement (cm)									
Tree no.	Species	a	b	c	d	e	f	g	h	i	datum
16 Killerton	Quercus robur	95	105	-	82	-	74	-	-	-	100
19 Killerton	Quercus robur	78	85	77	25	40	20	50	48	72	100
21 Llanhydroch	Quercus robur	110	125	-	55	-	15	120	-	100	-

a)Vertical root and ground displacement

		Horizontal position of vertical ground displacement (cm)								
Tree no.	Species	m	n	p	q	r	s	t	u	v
16 Killerton	Quercus robur	26	32	45	51	-	121	152	163	173
19 Killerton	Quercus robur	20	45	-	73	205	225	318	340	-
21 Llanhydroch	Quercus robur	50	-	100	150	-	240	370	420	450

b)Horizontal position of vertical ground displacement

Table 4.1 Measurements taken of partially lifted root-plates
(all parameters referenced by letters relate to those marked on Figure 4.5)

	Minimum	Mean	Maximum	No. of specimens	Missing values
Trunk diameter (cm)	15.0	81.3	170.0	37	0
Height (m)	5.0	16.7	26.0	37	0
Crown spread (m)	2.0	12.1	22.0	37	8
Root plate spread (m)	2.0	3.8	6.0	37	4
Root plate depth (m)	0.3	0.8	2.0	37	6

Table 4.2 Summary of survey data for the storm damaged trees

	Minimum	Mean	Maximum	No. of specimens	Missing values
Trunk diameter (cm)	60.0	98.3	160.0	6	0
Height (m)	12.0	20.3	26.0	6	0
Crown spread (m)	7.0	13.4	24.0	6	0

Table 4.3 Summary of survey data for the undamaged trees

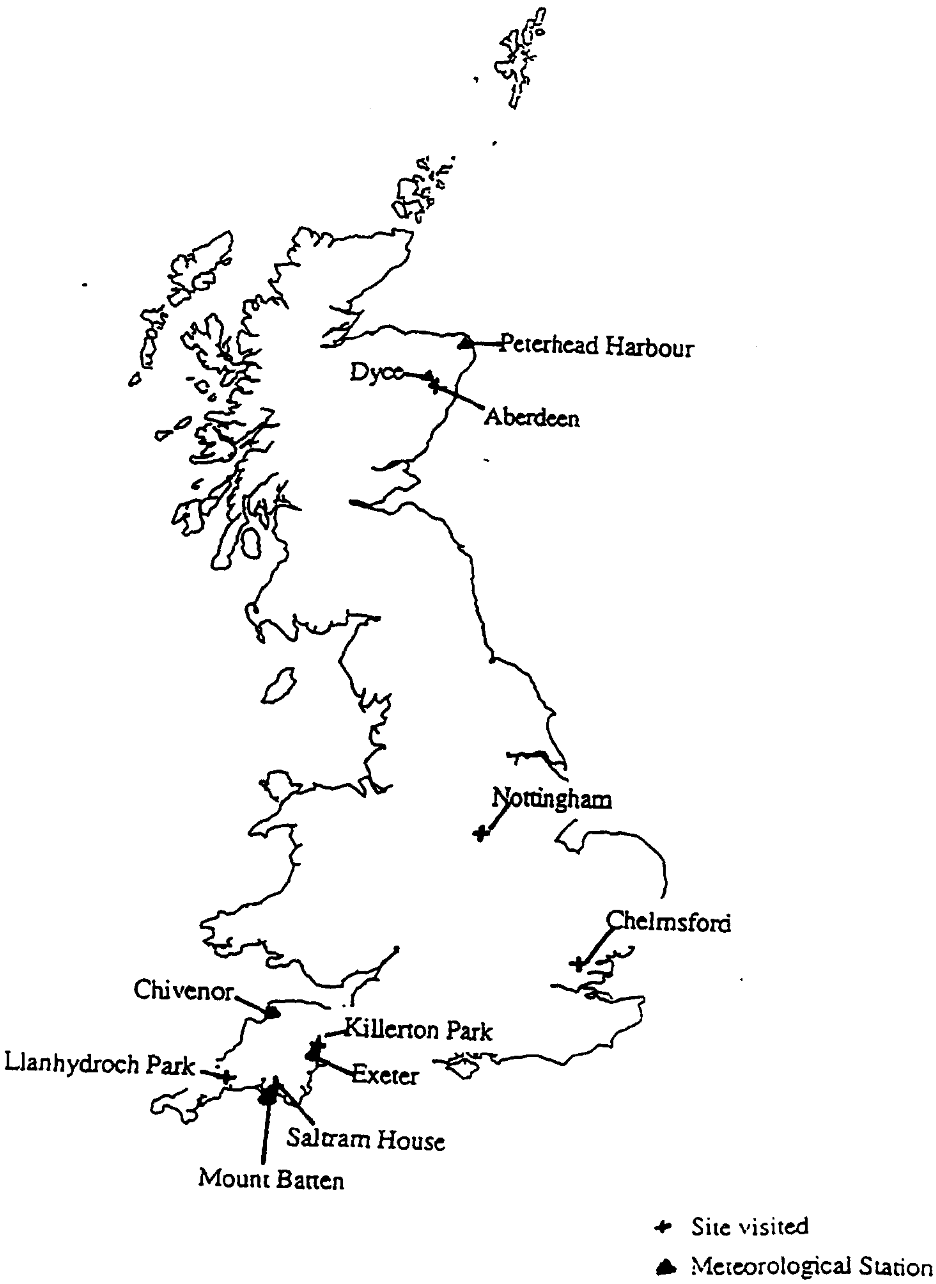


Figure 4.1 The survey sites and their nearest Meteorological station

Site		
Tree Number		
Species	:	English name, Latin name
Location -	:	street/ park/ hedgerow
Height (m)	:	
Crown spread (m)	:	maximum diameter of the trees canopy when projected to the ground.
Height to crown	:	the length of clear trunk from ground level to the lowest branch.
Trunk diameter (dbh) (cm)	:	maximum diameter of the trunk measured at 1.3m (breast height,).
Disease/Decay	:	presence of disease or decay.
Physical damage to roots	:	evidence of severance, compacted soil, root hindrance.
Root-Plate:-		
Maximum depth of roots (m)	:	maximum depth of root penetration or depth to which roots snapped.
Depth containing major laterals (cm)	:	depth of soil in which the major lateral tree roots are growing.
Depth of soil above roots (cm)	:	depth of surface soil layer below which lie the major laterals.
Horizontal root-plate diameter (m)	:	largest distance across the uprooted root system, to which soil is attached as one unit i.e. the soil/ root ball.
Horizontal roots protruding (m)	:	the length of roots protruding from the root-plate. Number of protruding roots may be given.
Vertical root-plate radius (m)	:	distance from centre of trunk to the highest point of the uprooted root-plate.
Vertical roots protruding (m)	:	length of roots protruding vertically from the root-plate. n.b. these are assumed to have been the windward roots.
Thickness of roots at snapping point (mm)	:	an example of diameters of roots at their breakage points. n.b. not a complete record of all roots.
Soil description	:	soil description in engineering terms. Agricultural descriptions used where engineering terms are lacking.
Other comments	:	

Additionally the following technical terms were used on the Aberdeen survey sheets (Appendix B) and may appear in 'other comments':-

Surrounding ground	:	description of ground cover and slope.
Crown spread - open/ dense	:	qualitative description of the crown density.
Asymmetrical growth	:	observation of crown shape.
Pollarded:	:	a process of cutting the trunk at 2-3m and allowing regrowth, often seen in *Platanus acerifolia*, *Tilia* etc.
Age - Y, SM, M, O	:	tree's age class - young, semi-mature, mature, over - mature.
Soil moisture content	:	the proportion of moisture contained in the soil by weight.

Figure 4.2 Survey sheet with explanation of parameters

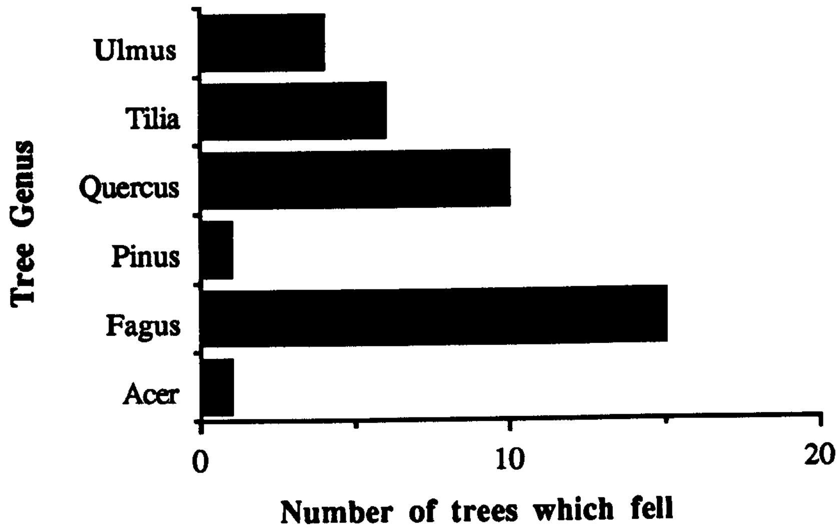


Figure 4.3 Tree genus of fallen trees

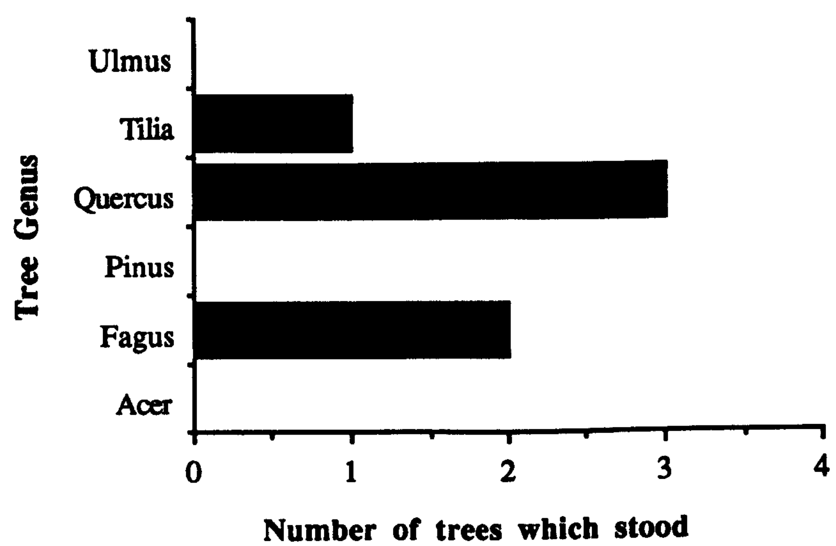


Figure 4.4 Tree genus of standing trees

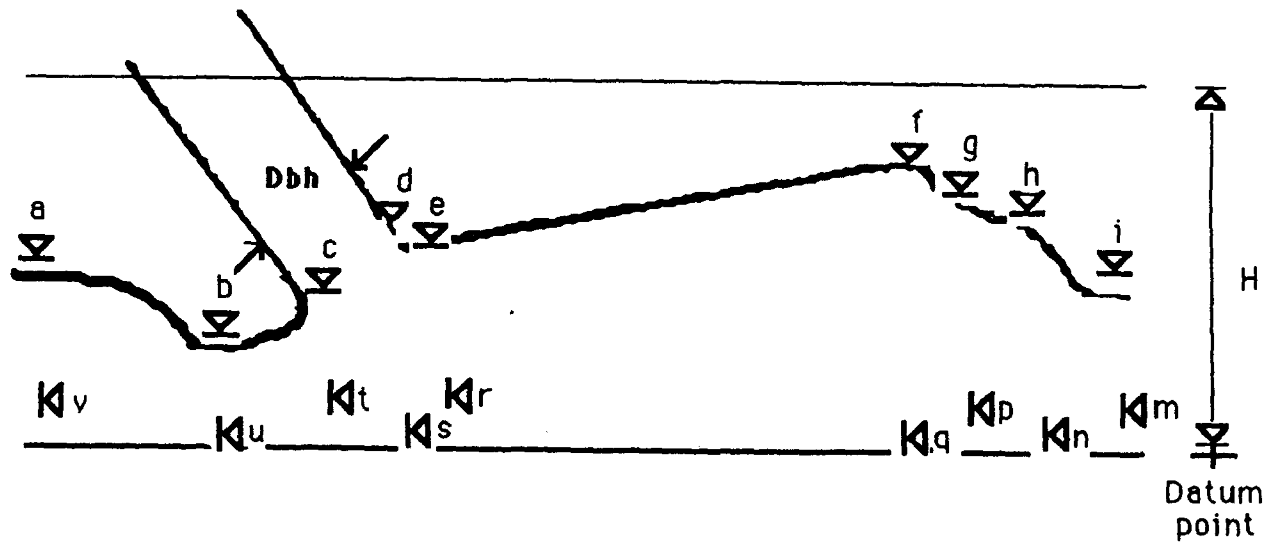


Figure 4.5 **Partial lifting of tree roots**

(measurements for four trees in Table 4.1)

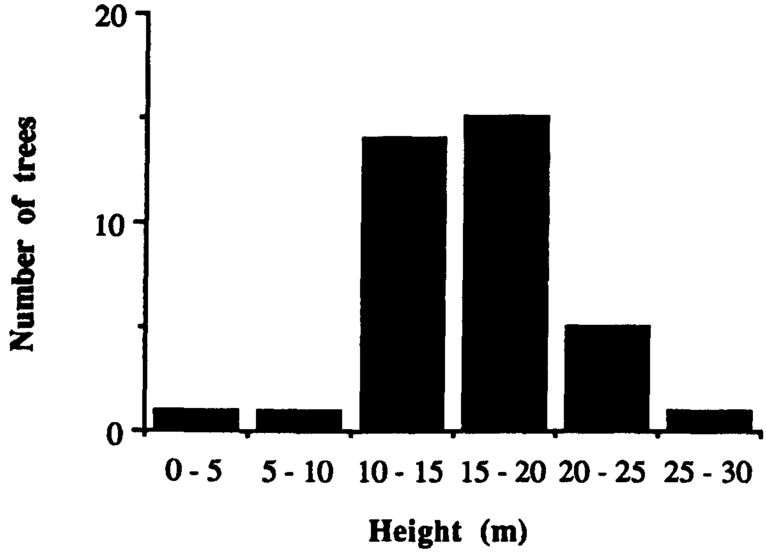


Figure 4.6 Heights of trees that fell

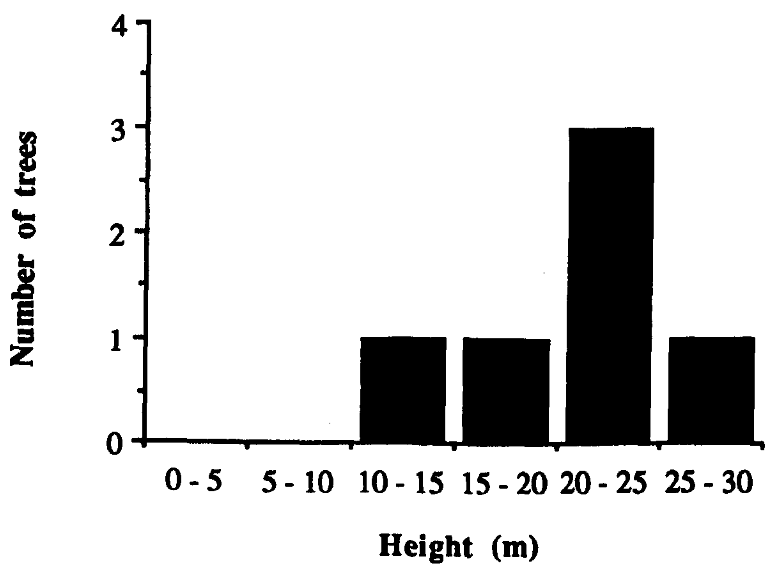


Figure 4.7 Heights of standing trees

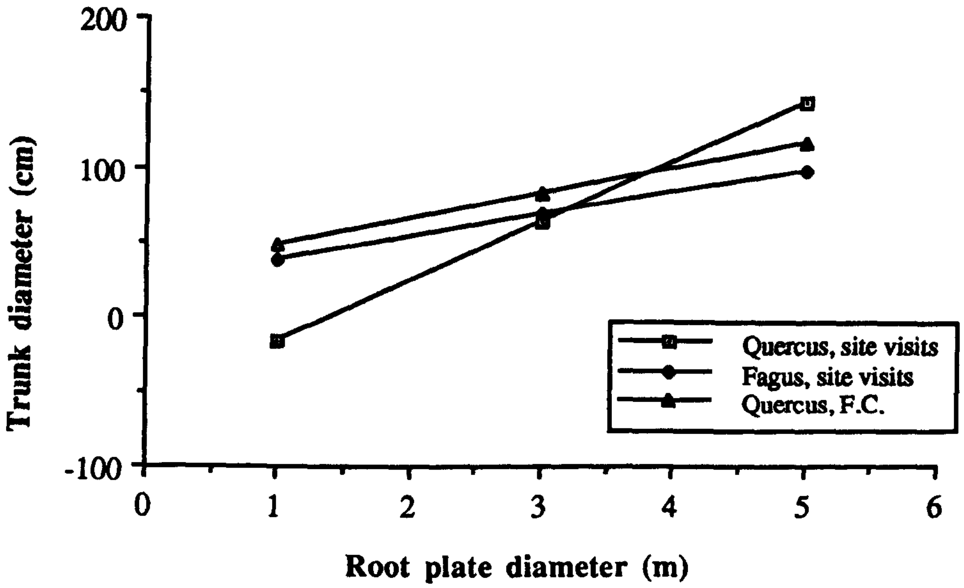


Figure 4.8 Aberdeen and SW England Quercus and Tilia
F.C. Quercus
Regression lines of trunk diameter versus root-plate diameter

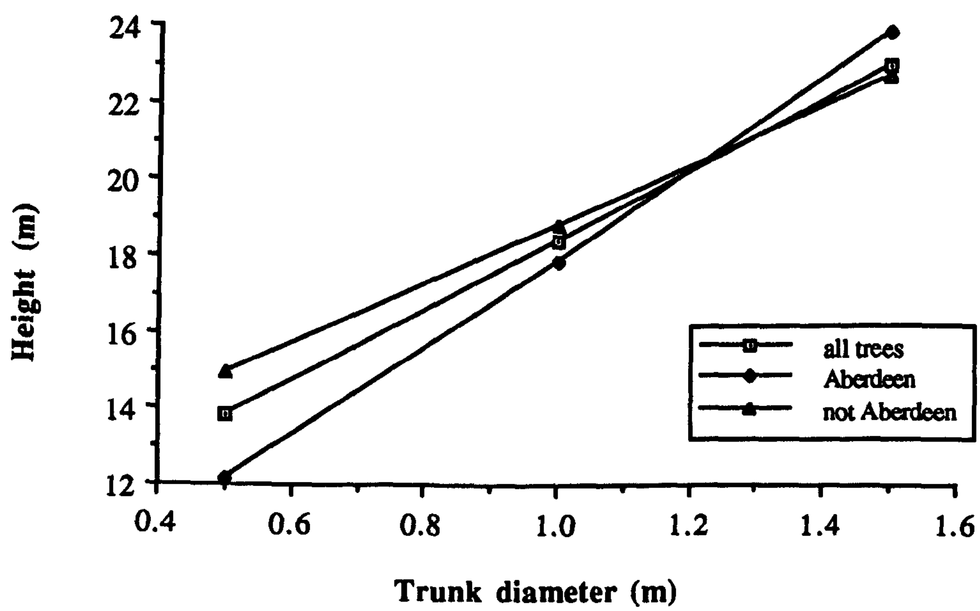


Figure 4.9 Aberdeen trees and SW England trees
Regression of tree height versus trunk diameter

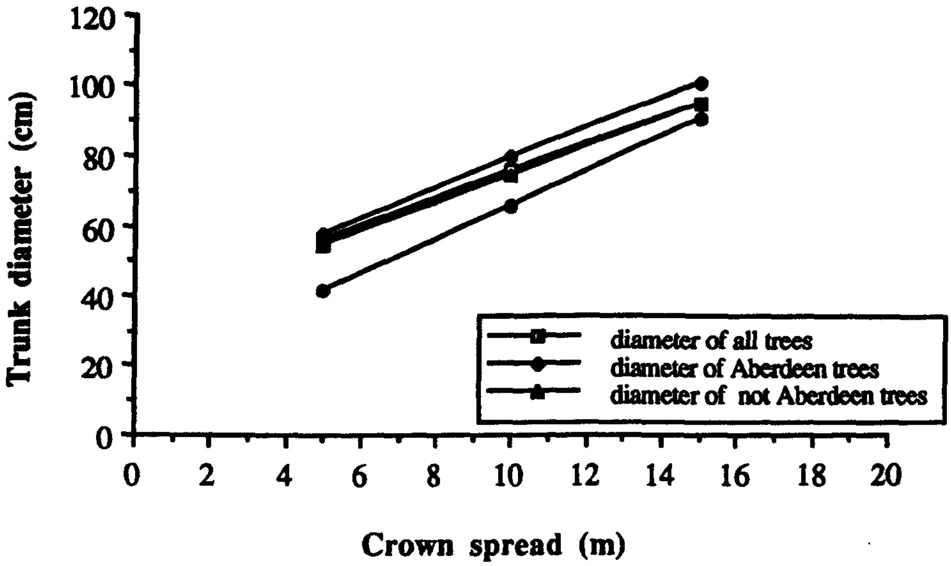


Figure 4.10 Aberdeen trees and SW England trees
Regression lines of trunk diameter versus crown spread

Plate 4.1 - Young *Quercus robur* uprooted, with *Quercus ilex* standing in the background.
Killerton Park, Tree no. 8, Appendix B

Plate 4.2 - Branch damage to a standing *Quercus*.
Hylands Park, Chelmsford, Essex

Plate 4.3 - Stem breakage of a *Fagus*
Killerton Park, Devon

Plate 4.4 - Failure at base of an *Aesculus*.
Killerton Park, Devon

Plate 4.5 - Root lift of a young *Quercus*
Killerton Park, Tree no. 16, Appendix B

Plate 4.6 - Partially uprooted *Quercus*.(Propped by an adjacent tree)
Llanhydroch Park, Tree no. 21, Appendix B

Plate 4.7 - Two fallen *Fagus* within a *Fagus* stand. Llanhydroch Park, Tree nos. 22 and 23, Appendix B (Tree no.24, Appendix B remained standing)

Plate 4.8 - Fallen *Populus* in rows of *Populus* and *Tilia*. Highfields Sports Ground, Nottingham

Plate 4.9 - Fallen *Quercus ilex*.
Killerton Park, Tree no. 1, Appendix B

Plate 4.10 - Storm-damaged young *Fagus*.
Aberdeen, Tree no. 8, Appendix B

Plate 4.11 - Fallen roadside *Fagus* with a partially decayed root-plate.
Aberdeen, Tree no. 4, Appendix B

Plate 4.12 - Large *Quercus* root-plate, showing root rot in the windward direction.
Killerton Park, Tree no. 7, Appendix B

Plate 4.13 - Basal rot of a *Fagus*.
Killerton Park, Devon

Plate 4.14 - Decay in the trunk of a *Tilia*.
Aberdeen, Tree no.3, Appendix B

Plate 4.15 - *Ulmus* root-plate.
Aberdeen, Tree no. 5, Appendix B

Plate 4.16 - Basal view of *Fagus* root-plate.
Aberdeen, Tree no.2, Appendix B

Plate 4.17 - Large *Fagus* uprooted :- very small root-plate. Aberdeen, Tree no. 11, Appendix B

Plate 4.18 - Uprooted *Quercus*:- multiple tap root. Killerton Park, Tree no. 15, Appendix B

Plate 4.19 - Basal view of *Fagus* root-plate.
(Tap root position located with a yellow pen)
Aberdeen, Tree no. 11, Appendix B

Plate 4.20 - Close-up of decayed tap root.
Aberdeen, Tree no. 11, Appendix B

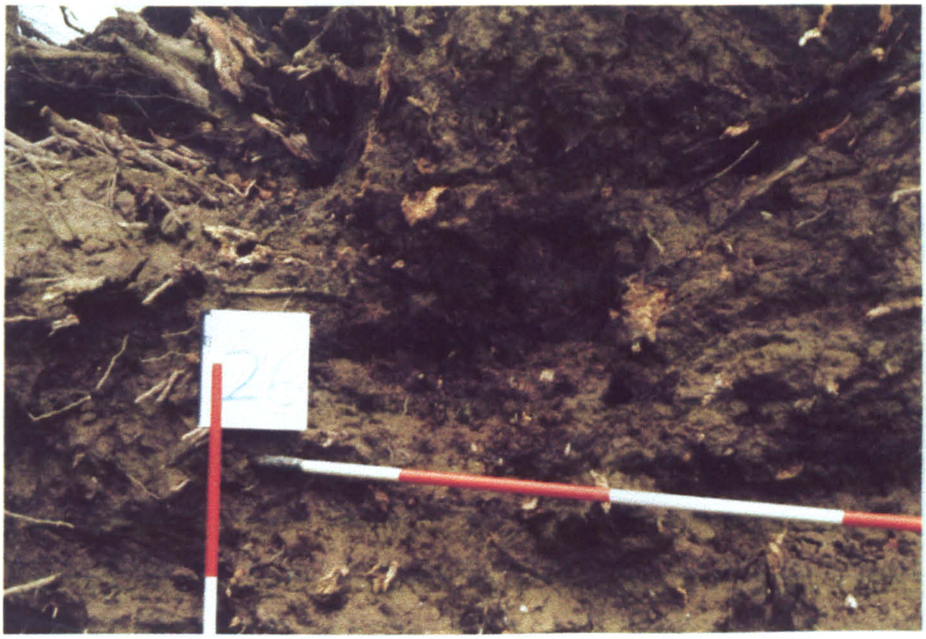


Plate 4.21 - Tap root of a *Quercus* and roots radiating laterally. Killerton Park, Tree no. 26, Appendix B

Plate 4.22 - Large uprooted *Fagus*, near to a drainage ditch. Erewash District, Derbyshire

Plate 4.23 - Large *Ulmus* with a small root-plate, surrounded by bituminous footpath.
Aberdeen, Tree no. 6, Appendix B

Chapter 5

Observations of Tree Movement in the wind

5.0 Introduction

The introduction (Section 1.0), which outlined the aims of the research, indicated that the objective was not only to determine the specimens susceptible to damage in strong winds, but also to investigate the mechanisms of tree stability and uprooting. Up to this point the mechanisms of tree stability have only been mentioned in the literature review (Section 2). It was suggested there, that uprooting involved dynamic movement, and not solely static loading. However little of the experimental work described in the literature review was directly related to broadleaf trees. Research by practical experimentation was therefore undertaken to increase this area of knowledge.

Due to practical difficulties in applying a mainly fluctuating load, observations and measurements were made on trees undergoing movement in the wind. Tree displacement and wind speeds were simultaneously monitored. This created an experimental situation which was not 'controlled' but reliant on the weather conditions. Wind speeds and gustiness were recorded but could not be generated on request. The success of the operation depended on the accuracy of the weather forecast and the ability of the researcher to respond, in order to set up the equipment in time to record the highest wind speeds and gusts. It was not expected that the selected specimens would be monitored during their ultimate failure, as the event of this occurring during monitoring would be both unlikely and if it did occur, very dangerous.

The aim of the experimental work was to investigate which wind speeds and gust frequencies cause the greatest dynamic motion of the tree, with the ultimate objective being to determine the weather conditions at which the tree is most unstable and likely to uproot. It was thought likely that the most damaging wind speed and gust frequency would correspond to the natural resonance frequency of the tree.

Details of the experimental set-up, procedure and analysis are described in Section 5.1, with the specimen tree selection being influenced by the findings of Chapter 3. Section 5.2 describes the proposed analysis to be carried out on collected data. However, after preliminary testing, little useful data was generated (Section 5.3), and so a further tree was selected for observation (Section 5.4). The preliminary results on this occasion proved this tree to be a more appropriate selection (Section 5.4.1). The tree was then monitored a further four times over a two year period. The full analysis was undertaken to generate values for the tree's damping coefficients and the natural frequency of oscillation of the tree (Section 5.5), with the ratio of tree displacement with wind speed also being calculated. These values were to be used in the determination of the tree's drag coefficients, with other values derived from load/ deflection curves produced in other experiments (Chapter 6). The results were then related to the time of year and leaf condition of the tree, and comparisons made between results (Section 5.6).

5.1 The Experiment

5.1.1 Initial Tree Selection

The selection of a tree or trees for monitoring in the wind was carefully considered and a number of criteria were specified which the ideal specimens would satisfy. These criteria included the tree species, the age and size of the tree, and the wind climate around the tree. One further restriction was the proximity of the tree to the Department. Tree selection was initially limited to trees on the University Campus, because of the need for a quick response which was required to maximise data collection in windy conditions.

In order that the experiment be of maximum value the species had to be common, both in the urban and rural situation The choice of species was directed by the results of the F.C. and Kew surveys (Chapter 3). A number of suitable species were identified as most commonly occurring. These were *Tilia*, *Fagus*, *Quercus*, *Acer*, and *Aesculus. Platanus, Betula* and *Fraxinus* were also regarded as being frequently occurring species. Of these species *Aesculus* and *Fraxinus* were deliberately avoided because of their tendency to suffer crown breakage as opposed to uprooting. Reservations were held about *Betula* also, due to apparent visual differences in tree form from that of other broadleaf trees. (The effects of tree parameters on the tree's physical behaviour are described in Section 2.1. Speculation about the general nature of tree response from an atypical tree species was felt to be inappropriate.

The size and age of the tree was the second factor to be considered. These parameters are also reported to affect the tree's behaviour, Section 2.1. Young trees are generally more flexible and probably give greater relative deflection in the wind, but the interest lies primarily with the larger tree which causes more damage when uprooted. The development of the root-plate, (hypothesised in Section 4.3.3) suggests that the younger tree may not resemble the older tree in this area either. Since the interaction of the wind, with the tree's crown, trunk, and root-plate was to be observed, it was decided that semi-mature or mature trees should be selected.

The precise location of the tree in terms of wind exposure was the next consideration. The requirement was for the tree to be reasonably exposed, preferably to the prevailing wind, from the South West. A clear fetch was desired to provide a relatively simple wind profile, though it was felt that a few obstacles would not be a problem. Indeed such obstacles may increase the gustiness of the wind, but may also reduce the wind speed. In the urban situation, the winds are subjected to greater surface roughness effects caused by the presence of all the buildings. The trees most at risk in this situation would probably be those growing where the wind is channelled along a confined narrow gap. It is hoped that a suitable urban tree may be studied at a later date.

An ideal tree would also be isolated in terms of its crown being able to move freely without interaction from surrounding trees and buildings which may introduce external damping to the system.

With these criteria in mind, two trees were initially selected for instrumentation and observation. Neither were ideal, but they were the specimens found which matched the criteria most closely .

The *Acer pseudoplatanus* (Plate 5.1), was an isolated tree situated on the brow of a hill. It was 20 m high and had a diameter at breast height of 86 cm. It was perhaps older than would be ideal, and slightly sheltered from the prevailing South Westerlies by the trees on the adjacent hill (Plate 5.2).

The second specimen was a *Fagus sylvatica* (Plate 5.3) of height 18 m and breast height diameter of 51 cm. It was younger than the *Acer*, with a more open fetch (Plate 5.4). Its branches were however in slight contact with neighbouring trees, and the tree itself had a crown containing three leaders, as oppose to the more usual single leader. This latter factor would increase the damping effect from within the tree itself. It was thought however that interest may be added to the experiment in the observation of the individual leaders and in the investigation of how they behave in relation to each other.

A map of the University campus shows the precise location of all the trees studied as part of this research (Fig. 5.1).

5.1.2 Instrumentation

Wind measurements were required simultaneously with measurements of the tree itself. It was decided to monitor the trunk movements, and movements of the root-plate.

Wind measurements were made using a 'LEDA' triaxial propeller anemometer. That enabled the wind speed to be measured in three directions:- directly into the wind, and at 90° to the wind, in both a horizontal and in a vertical direction. The anemometer was located beside the tree, in such a position that it did not interfere with the wind flow incident on the tree, and at a height approximately equal to the centre of the tree's crown (Plate 5.5). At first the anemometer was mounted on a scaffold tower, but later a hydraulic mast was used which eased equipment assembly and allowed finer adjustment to the positioning of the anemometer heads into the wind. Each head was calibrated so that the output signals could be translated into wind speed data. The calibration was carried out in the controlled environment of the wind tunnel, using an inclined water manometer as the standard reference for calibration (Appendix C).

The trunk displacement was measured with linear transducers, attached to the tree by a series of eye hooks, swivels, split rings, fishing trace wire and a pulley (Fig. 5.2). This apparatus was implemented following discussion with Dr. B. Gardiner of the Forestry Commission, who was making similar measurements of conifer trees. Trace wire of 15 lb or 20 lb breaking strain was used as it was found to be suitably strong and responsive to tree movement without being so heavy to cause sagging due to its own weight. The linear transducers were set so they could record movement in either direction. Each transducer was calibrated individually in the laboratory, for conversion of the output into trunk displacement (Appendix C). Eye hooks were positioned in the tree at four places, though in any one test only two positions were used at any one time. For actual tree movement to be calculated, the height of the eye hooks and the angle of the trace wire were measured (an example calculation is given in Appendix E).

Problems were encountered in positioning the eye hooks for the trunk displacement measurements. Care had to be taken to ensure the trace wire was not obstructed by tree branches at any time during monitoring (despite some minor pruning). This meant that predetermined heights could not be set and even the eye hooks which were at 90° to each other on the trunk may have had a slight vertical displacement.

Root and root-plate movement were monitored with the use of linear potentiometers (Fig. 5.3). The basis of this apparatus was a stake holding the linear potentiometer at a fixed reference point. It was driven into the soil to a depth of either 1.3 m where possible, or 0.9 m if the ground prevented deeper penetration. This was estimated to be below the bulk of the root-plate. The stake was protected within a plastic sheath so that any movement of the root-plate would not move the stake. A small 'plate' was placed on the surface of the soil with the nail 6.5 cm long, penetrating the soil, and the flat plastic head located on the soil surface. Any movement of the root-plate was expected to cause the plate to move in relation to the stake. This movement was recorded by the linear potentiometers. The linear potentiometers were again calibrated (Appendix C) so the voltage output could be converted to root-plate displacement in millimetres.

The linear potentiometers were located around the base of the tree in the prevailing wind direction and at 90° to it. It was hoped to establish not only the size of root-plate movement corresponding to the wind speeds, but also a profile of the root movement at varying distances from the tree trunk.

Difficulties were also experienced in locating the linear potentiometers. The large stake and sheath had to be positioned in an area free of tree roots or stones. A moveable arm on the clamp holding the potentiometers however meant that the predetermined positioning could be maintained in most instances.

The general layout of the positioning of the instruments in relation to the tree is shown in Figure 5.4. The exact location of the linear transducers and eye hooks with angles of the trace wire were recorded with the linear potentiometers positions for each tree (Appendix D).

All the instruments produced voltage outputs which were transmitted to a Campbell Scientific CR10 Datalogger. They were then converted with appropriate calibration to produce either wind speed measurements, or values of trunk or root-plate displacement. The datalogger had twelve input channels for single-ended voltage signals. Three channels were used for the anemometer readings, two for the linear transducers, and six available for linear potentiometers. One channel was unoccupied. The datalogger was programmed to take readings at time intervals of multiples of 1/64 second. Readings were initially taken every eighth (1/8) of a second. This particular time interval was chosen as it was approximately ten times faster than the expected frequency of resonance of the tree, around 0.2 to 1.0 Hz (Section 2.2.3). One eighth of a second gave a frequency of resolution of 8 Hz. With the data logger taking readings on eleven channels at this rate the storage module on the logger could hold up to 14 minutes of continuous data. This was then downloaded on to a portable Amstrad computer, model PPC 640, and the datalogger restarted for logging.

5.2 The Analysis

5.2.1 Simple analytical procedures

Data sets were split using a FORTRAN program which assigned each datalogger channel to a separate file. From these files, time series graphs of wind speed, tree displacement, and ground movement were plotted. The graphs presented the data in a form which certain simple results could easily be seen, for example the maximum values and the general time history of each parameter. Comparison of a wind speed graph with a tree displacement graph would enable the 'cause and response' to be investigated and perhaps establish the threshold values required to initiate tree movement. The movement of the root-plate was also observed by plotting time series graphs, and the results were discussed. This completed the simple analysis to assess the suitability of the tree for more complex analysis.

5.2.2 Further analysis

Minute averaging was undertaken of both the wind speed and tree displacement data. This simplified the data by averaging out sudden wind gusts and removed any erratic data values. The tree's response to the wind was plotted as time series and their phasing investigated.

Further to this the minute averaging of the tree displacement values were plotted against the wind speed. This generated ratio values of tree displacement in the wind which were used to estimate of the absolute trunk resting position.

These graphs of wind speed against trunk displacement were also used in the determination of the drag coefficient, which will be described in Chapter 6.

5.2.3 Power spectra - wind parameters

Further analysis required a second FORTRAN program (adapted from a program written by Coleman 1990) to run Fast Fourier Transforms on the data files and produce power spectral densities. These graphs describe the energy content of the different frequency bands of the wind. Typically there is more energy at the lower frequencies producing a curve as shown in Figure 5.5, though the peak moves towards the higher frequencies with increasing wind velocities.

The power spectral density of the wind could then be fitted to the von Karman spectrum, a model which describes the wind energy at specific frequencies. It is given by:-

$$\frac{n.S(n,z)}{\sigma(z)^2} = \frac{4\,[\,{}^{x}L_v(z)\,n \;/\; \bar{v}(z)\,]}{[\,1 + 70.8\,(\,{}^{x}L_v(z)\,n \;/\; \bar{v}(z)\,)^2\,]^{5/6}} \qquad 5.1$$

(ESDU 1974)

where:- ${}^{x}L_v(z)$ is the streamwise turbulence length scale, **z** is the height above ground level, **n** is the frequency, **S(n,z)** is the power spectral density, σ is the r.m.s. wind velocity, and $\bar{V}$ is the mean wind velocity.

The power spectra of the wind would be expected to fit such a curve (ESDU 1974). The fitting of the curves requires the selection of the best fitting of a number of curves of different of varying turbulence length scale (The average length of the gusts present in the wind). Once a von Karman curve has been selected the corresponding turbulence length scale can then be related to the surface roughness (z_o) of the local ground environment (for example urban, forest or open countryside). ESDU (1974) present a table of typical values of the surface roughness parameter (z_0), with a description of the terrain several kilometres upwind of the site.

To simplify the determination of the turbulence length scale, and minimise the laborious fitting of numerous von Karman spectra, the peak of the spectrum is given by:-

$$n_p\,{}^{x}L_v \,/\, \bar{v} = 0.146 \qquad 5.2$$

where $\bar{v}$ = mean velocity, n_p = peak frequency value and ${}^{x}L_v$ = length scale. The peak frequency value can be determined simply from the wind's spectrum, and so after calculating the mean velocity, the length scale can be determined.

Turbulence, the variable component of the wind, not only has a length scale but also an intensity. This is defined as the ratio of the square root of variance of the instantaneous velocity to the mean wind speed. This value can again be related to the surrounding surface roughness (ESDU 1974).

These parameters were calculated and used to assess the properties of the winds measured during the experiment.

5.2.4 Power spectra - tree displacement parameters

The power density spectrum of the tree displacement showed the basic von Karman curve, but with an additional peak in the high frequency range. This peak is more clearly seen by dividing the tree's power spectrum by its corresponding wind speed spectrum to produce an admittance. This was achieved by selecting specific values on the tree displacement spectrum and dividing them by their corresponding values on the wind spectrum, and plotting the result. Computer technology was not employed for this as a great amount of filtering of the data would have been required to obtain clear results.

The frequency of the peak, shown on the admittance spectrum, is the natural frequency of oscillation of the tree. It is the frequency at which the tree amplifies the wind energy input to produce a magnified output.

Damping of the tree is a further parameter to be investigated. The tree removed from its resting position by the wind oscillates at a specific frequency eventually returning to its original position if no further displacing forces are applied. This response can be described mathematically considering Newton's 2nd law:- mass x acceleration = applied force. The force applied to the tree is a function of the stiffness, damping, tree displacement, velocity, and a periodic oscillating force as shown in equation 5.3, a damped harmonic response :-

$$M\frac{d^2x}{dt^2} = -sx - \lambda\frac{dx}{dt} + Y\cos(\omega t) \qquad 5.3$$

where **M** = mass, $\frac{d^2x}{dt^2}$ = acceleration, **s** = stiffness, λ = damping, $\frac{dx}{dt}$ = velocity and **Ycos(ωt)** is the periodic oscillating force.

By convention one can write :-

$$\omega_n = \sqrt{\frac{s}{M}} \qquad \frac{2c}{\omega_n} = \frac{1}{s} \qquad K = \frac{1}{s}$$

where ω_n = natural radial frequency of oscillation, **c** = damping coefficient, and **K** is a coefficient.

If the solution is $x = X \cos(\omega t - \phi)$, where ϕ is the phase angle difference, then the variation of X/ KY has been closely studied. Graphs have been produced from which values of damping coefficients may be generated, (Fig. 5.6, Prentis 1970).

To determine the damping coefficient of the tree the ratio a/b (Fig. 5.7), (where **a** is the amplitude of the tree's resonant peak, and **b** is the amplitude of the spectrum at the same frequency if there were no resonant peak), corresponds to X_{max} / KY in equation 5.4.

$$\frac{X_{max}}{KY} = \frac{1}{2c\sqrt{1 - c^2}} \qquad 5.4$$

Values of **a** and **b** can be determined from the displacement spectra and substituting in equation 5.5.

$$\frac{a}{b} = \frac{1}{2c\sqrt{1 - c^2}} \qquad 5.5$$

This equation can then be multiplied up and expressed as a quadratic in c^2, which can be solved to give the expression 5.6.

$$c = \frac{1}{\sqrt{2}} \sqrt{1 - \sqrt{\left(1 - \frac{b^2}{a^2}\right)}} \qquad 5.6$$

The value of **c** (damping coefficient) can be then calculated.

If $\frac{a}{b}$ is large however (greater than say 5 to 10), then the value of c can be approximated as in expression 5.7.

$$c \approx \frac{1}{\sqrt{2}} \sqrt{1 - \left(1 - \frac{1}{2}\frac{b^2}{a^2}\right)} \quad \text{simplifying to} \quad c \approx \frac{1}{2}\frac{b}{a} \qquad 5.7$$

5.3 Results of *Acer* and *Fagus* monitoring

5.3.1 The *Acer*

The *Acer* was monitored on the 30th January 1990 when a maximum wind speed of 6.6 ms^{-1} was recorded. The time series graphs for both the wind speed and the tree displacement were drawn (Figs. 5.8 and 5.9). These show the peaks in the both graphs to be flattened. In the case of the tree displacement these flattened peaks highlighted a trend throughout the data in which the tree displacement was seen to occur in steps and have periods of up to a minute without the trunk moving. This probably occurred due to a combination of the wind speeds not being very strong, and the large tree requiring large forces to overcome resistance.

The flattening of the wind speed peaks however, indicates an actual problem with the datalogging. The voltage input was multiplied in the datalogger to give a wind speed output, but numbers were created that were larger than could be handled by the datalogger and hence the output was truncated. This indicates that wind speeds greater than the recorded 6.6 ms^{-1} may have been incident on the tree. For future readings the internal multiplier of the datalogger was returned to 'multiply by 1', and calibration implemented later in the data analysing process.

Comparison of corresponding trunk movement and wind speed time histories showed the tree to follow the wind speed fluctuations to some extent, though not all the peaks and troughs were identically matched. It was difficult to pin-point critical wind speeds which initiated trunk movement.

The inertia of the tree proved a problem when the power spectral densities were considered. The frequency of spectral peaks was likely to record the frequency of when the tree actually moved, rather than the frequency of the tree movement itself. Because of this, the wind and tree deflection spectra were not closely studied. It was noted however, that neither spectra showed much energy at frequencies above 1 Hz. As the recording frequency needs only to be four times that of the frequency of the recorded movement, then this result suggested that readings need only be taken every 1/4 second. This would effectively double the time length of the data set, and still give a good frequency resolution, of up to 4 Hz, a valuable point to note and adopt for future experiments.

5.3.2 The *Fagus*

The *Fagus* was monitored on the 22nd of February 1990. The results were similar to the *Acer*, with frequent stationary periods between periods of trunk movement. These results were again not satisfactory for further analysis.

5.4 The revised experiment

5.4.1 Introduction

The small movements monitored on the *Acer* and *Fagus* were not satisfactory results on which to base the planned analysis, so another specimen was selected for observation. A *Platanus acerifolia* (London Plane), (Plate 5.6) whose trunk moved visibly in the wind was chosen. It was a much younger tree, 9.2 m high with a breast height diameter of 153 mm, and was growing at the top of a grassy slope with a clear fetch open to south westerly winds (Plate 5.7).

The experimental apparatus was arranged as described for the earlier specimens (Section 5.1.2), with the two eye hooks both fixed in the direction of the prevailing wind, at different heights. One slight alteration was made however in the recording process, the wind speed was recorded by the datalogger as the millivolt output from the anemometer and not converted into metres per second until a later stage. This would eliminate the problems of maximum values experienced in earlier testings.

The analytical procedures followed were those described in Section 5.2.

5.4.2 Results of initial testing of the *Platanus*

The *Platanus* was first monitored on the 6th September 1990. Wind speeds during the recording period peaked at 9.7 ms^{-1} with a mean of 5.7 ms^{-1}. This was sufficient to keep the *Platanus* in constant motion (Fig. 5.13b), which meant that the displacement spectra would be expected to be representative of the actual tree motion unlike those generated earlier by the *Acer* and *Fagus*.

This observation and the results of further analysis deemed the experiment both successful and informative. It was therefore decided that resources be concentrated on this *Platanus* alone and as much data as possible collected.

5.4.3 Further observations of the *Platanus*

The *Platanus* described in Section 5.4.1 was the subject of all the observations that follow. The tree was monitored in total on five separate occasions (including the preliminary testing), in differing seasons of the year:- the 6th September 1990, the 19th September 1990, the 15th January 1991, the 24th September 1991, and the 10th March 1992. Whether the tree was in leaf or not, was noted at each recording date. In an ideal situation the tree would have been monitored at regular intervals throughout the year, but the nature of the experiment meant that monitoring only occurred when strong winds were forecast.

On each of the above dates, data was recorded in a number of 14 - 25 minute periods. All the data was screened and the recording sessions which recorded maximum wind speed values on each occasion were selected to represent the days' data collection. A note was also made of any increase in the tree's dimensions over the two year recording period.

The basic layout of apparatus was as described in Section 5.2.2, with trunk displacement being measured at 5.23 m and 3.27 m. The precise layout for each recording session is given in Appendix D.

5.5 Results from the campus *Platanus*

In the following results, reference is made to each day of data collection, and correspondingly values are given for each parameter calculated. One data set only, however was selected to represent the tree when it was in leaf and one to represent its out of leaf response. This illustrates the tree's differing response without unnecessary repetition.

The wind, which was recorded in 3 directions, is considered initially to assess its conformity to the expected parameters of turbulence intensity and length scale. The response of the tree will then be investigated, first by considering root movement, and then trunk displacement.

5.5.1 The wind

Wind speed was measured in three dimensions, in the direction of the prevailing wind, across the prevailing wind, and in a vertical direction. The mean wind speed and maximum gust value recorded, in the prevailing wind direction, for each day of monitoring are given in Table 5.1. For the day in which the maximum wind speed was recorded, the wind's properties in all directions are studied as an example to assess whether the wind has normal / expected properties.

The maximum wind speed was recorded on the 15th January 1991 with a gust of 14.5 ms^{-1}, and a mean wind speed of 6.3 ms^{-1}. It was noted that the maximum gusts recorded, occurred during the winter, when the tree had no leaves. There was also a tendency for the mean wind speed to be greater in winter. The variation in the maximum and mean wind speeds recorded throughout the year showed the extremes to vary by 4.8 ms^{-1} and 1.2 ms^{-1} respectively. This is an expected result correlating with the wind speed factor used in building design (Cook 1985).

The wind speeds measured on the 15th January 1991 were used to illustrate the wind in all three dimensions (Table 5.2). Figure 5.10, show the spectra for the wind in each direction. These curves were then simplified by averaging every 3 seconds (Fig. 5.11), to clarify the numerical data taken from the graphs. The length scales and the turbulence intensity values were calculated from these graphs (Table 5.2), it being assumed that length scales in each direction could be obtained from equation 5.2. Length scale values of 30.7 m, 13.1 m and 10.2 m for directly into the wind, across the wind and vertically respectively are all of acceptable orders (Cook 1985). The turbulent intensity values are also close to the expected values confirming that the wind incident on the *Platanus* was of usual form with no gross abnormalities.

The fitting of the curves for the determination of length scales, even on the simplified graphs remains very judgmental and has a large error margin. For example for the January 1991 results, in the direction of the wind, the frequency curve may be judged to peak anywhere between 0.2 Hz and 0.4 Hz. Consequently a variation in length scale of 23 m to 46 m could be the result. The result still remains within the accepted order whichever value is judged most correct.

Turbulence intensity and length scales values in the direction of the wind were similarly calculated for all the recording sessions (Table 5.2). Turbulent intensity values for the prevailing wind direction varied from 0.29 to 0.37, averaging at 0.33. The length scales vary from 20.4 m to 30.7 m. Both sets of values are within the acceptable ranges respectively, adding credibility to the results.

The spectra also showed that there was very little energy in the wind at frequencies greater than 1 Hz. This was apparently irrespective of the time of year.

5.5.2 Root-plate movement

No significant root-plate movement was measured during monitoring sessions, probably because the wind speeds were too low.

5.5.3 Trunk displacement

5.5.3.1 Time series analysis

Trunk displacement was observed to vary with fluctuations in the wind speed. Time histories of the trunk displacement and wind speeds showed the trunk to respond to increased wind speeds with increased deflection. The time histories are complex however, and not all the short changes are matched with tree movement. Minute averages of the wind speeds and trunk displacements were also plotted to simplify the results (Fig. 5.12). These showed very similar patterns to be traced by both the wind speed and trunk deflection.

On the 6th September 1990, when the tree was in leaf, winds were observed to peak at 9.7 ms^{-1} which induced a maximum of approximately 600 mm of measured trunk deflection (Fig. 5.13). Data collected on the 15th January 1991, when the tree was out of leaf, showed higher wind speeds some greater than 14 ms^{-1}, but less trunk deflection with a maximum of just over 200 mm (Fig. 5.14).

It should be noted that the trunk deflection values on the above mentioned figures, describe the tree deflection from the mean value of trunk deflection in each data set. This is adequate to describe the general response relationship to the two parameters, but an absolute value is required to calculate wind load and corresponding trunk deflection. The absolute position of trunk at a zero wind speed could not be measured as the apparatus was assembled on each occasion during the high wind speeds. An estimate of this absolute value for each recording session was calculated by plotting the minute averages of all the trunk deflection values (Table 5.3) against their corresponding wind speeds, and extrapolating a line of best fit to a wind speed value of zero (Fig. 5.15), it being assumed that a linear velocity/ displacement relationship existed (see below).

A further investigation was carried out (also reported in Roodbaraky et al 1994) to determine if the drag of the tree in the wind was proportional to the wind velocity squared, as for solid structures, or if the drag varied linearly with wind velocity due to the streamlining of branches and leaves as suggested earlier (Section 2.2.2). It was assumed that the deflection characteristic of these graphs could be represented by a curve of the form:-

$$x = a + bV^m \qquad 5.8$$

If the drag varied with the wind velocity squared then, since deflection is proportional to drag, m = 2 should provide the best fit. However if the drag varied linearly with velocity then m = 1 should appear the better fit. Curve fits were carried out for values of m of 1 and 2 and the root mean square (rms) residuals were calculated (Table 5.4). The results showed the values of the residuals to be very similar for the two values of m, with surprisingly m = 2 being a marginally, though not significantly, better fit. This was the result when the tree had leaves and also when it did not. It was noted however, that the earlier experiments carried out by Fraser (1962) and Mayhead (1973a) which found a linear relationship between wind velocity and drag, were obtained from the wind tunnel testing of smaller trees at substantially higher wind speeds. Consequently an equation for tree drag coefficient was derived (Section 6.5), but the calculation of drag coefficients required further experimentation to establish a load/ deflection curve for the tree. These were undertaken and described with corresponding results in the following chapter (Chapter 6).

5.5.3.2 Spectral analysis

Trunk displacement spectra were produced which in general followed the form of the wind spectra. They did however contain a spectral peak which was not matched on the wind spectra. This peak, which was thought to indicate the frequency of natural oscillation of the tree, was always at a high frequency but varied between recording sessions (Table 5.5). Data from 6th September 1990, with the tree in leaf produced a spectrum with a marked resonant peak around 0.25 Hz (Fig. 5.16b) when compared with its corresponding wind spectrum (Fig. 5.16a). With the tree out of leaf, 15th January 1991, the peak observed was more distinct and at the higher frequency of 0.8 Hz (Fig. 5.17). It is noted that the undamped natural frequency would be slightly higher than these values. However, the change is only significant when the damping ratio is around 0.2 or above (when the tree is in full leaf), and even then, would only reduce the frequency by a multiplication of approximately 0.95. This difference is effectively less than the error margins involved in the initial calculations of both the natural frequency and damping ratio.

The admittance confirmed these observations (Fig. 5.18), and also showed the spectral peak of the tree out of leaf to be of greater value over a smaller frequency band than the tree in leaf. This later point suggested that there was a difference in the amount of damping of the two systems. Greater damping was suspected in the case of the tree in leaf, as the oscillations were recorded over a greater range of frequencies, with less occurrence at each particular frequency.

Values of the damping coefficient of the tree calculated from the spectra are given in Table 5.5. A damping coefficient of 0.25 was determined for the tree in leaf and 0.08 for the tree out of leaf.

5.6 Conclusions

Higher wind speeds were recorded in the periods when the tree was out of leaf, i.e. the winter. It was also noted that in the winter the wind was found to have more energy at the higher frequency range than it did in the summer recording sessions, though the maximum frequencies at which energy was recorded were approximately the same.

The tree was however seen to deflect more in lower wind speeds when it had leaves, than in the higher wind speeds when it was without leaf.

The tree without leaves was found to have a higher natural frequency of oscillation with a much lower damping ratio than the tree with leaves.

The tree deflection/ wind ratio, natural frequency of oscillation and damping coefficients were all found to be related.

It may be hypothesised that the tree has developed the ability to vary such parameters as a defence mechanism for survival from windblow. Were the tree to maintain its high deflection to wind ratio in the winter when stronger winds were expected, damage would most probably ensue. Also, and not unrelated, if the natural frequency of oscillation of the tree, were to remain at the lower frequency values, recorded whilst it had leaves on, the increased energy of the wind at these frequencies in the higher winds, would again increase the likelihood of failure.

Tables : Chapter 5

Date	max wind speed (ms^{-1})	mean wind speed (ms^{-1})	Longitudinal Turbulence intensity	Length scale (m)
6th Sept 1990	9.7	5.1	0.320	24.8
19th Sept 1990	11.3	6.1	0.294	22.3
15th Jan 1991	14.5	6.3	0.366	30.7
24th Sept 1991	12.1	5.6	0.316	20.4
10th March 1992	13.8	6.0	0.369	29.2

Table 5.1 Wind data (into anemometer head): wind speed, turbulence intensity, length scale
N.B. the max wind speed is the maximum value recorded at any one quarter of a second.

Wind direction	max wind speed (ms^{-1})	minimum wind speed (ms^{-1})	mean wind speed (ms^{-1})	Turbulence intensity	Length scale (m)
Into head	14.5	0.0	6.3	0.366	30.7
Across head	1.88	-10.6	-4.0	0.487	13.1
Vertical	3.46	-5.8	0.6	1.746	10.2

Table 5.2 Wind data for 15th January 1991, speeds, turbulence intensities and length scale, in the three dimensions. N.B. maximum and minimum wind speed values are single values recorded in a quarter second period.

Date	Max. recorded tree deflection (mm)	zero correction (from ratio graphs) (mm)	Corrected tree deflection (mm)	Leafiness of tree
6th Sept 1990	352	293	645	full
19th Sept 1990	353	29	382	full
15th Jan 1991	168	33	201	none
24th Sept 1991	197	160	357	full
10th March 1992	161	87	248	none

Table 5.3 Tree Deflections in the wind

Test date	m value	a (mm)	b	rms residual (mm)
15th January 1991	1	-32.8	6.93 mm/ms^{-1}	14.3
15th January 1991	2	-18.6	0.739 mm/(ms^{-1})^2	13.6
6th September 1991	1	-150.4	28.4 mm/ms^{-1}	27.6
6th September 1991	2	-78.0	2.69 mm/(ms^{-1})^2	27.4

Table 5.4 Curve fit parameters to tree displacement wind speed data for the campus *Platanus*

Date of test	Natural frequency (Hz)	Damping ratio	Leafiness of tree
6th Sept 1990	0.25	0.20	full
19th Sept 1990	0.55	0.10	full
15th January 1991	0.80	0.05	none
24th Sept 1991	0.50	0.25	full
10th March 1992	0.8	0.08	none

Table 5.5 Natural frequency and damping ratios for campus *Platanus* calculated from displacement spectra

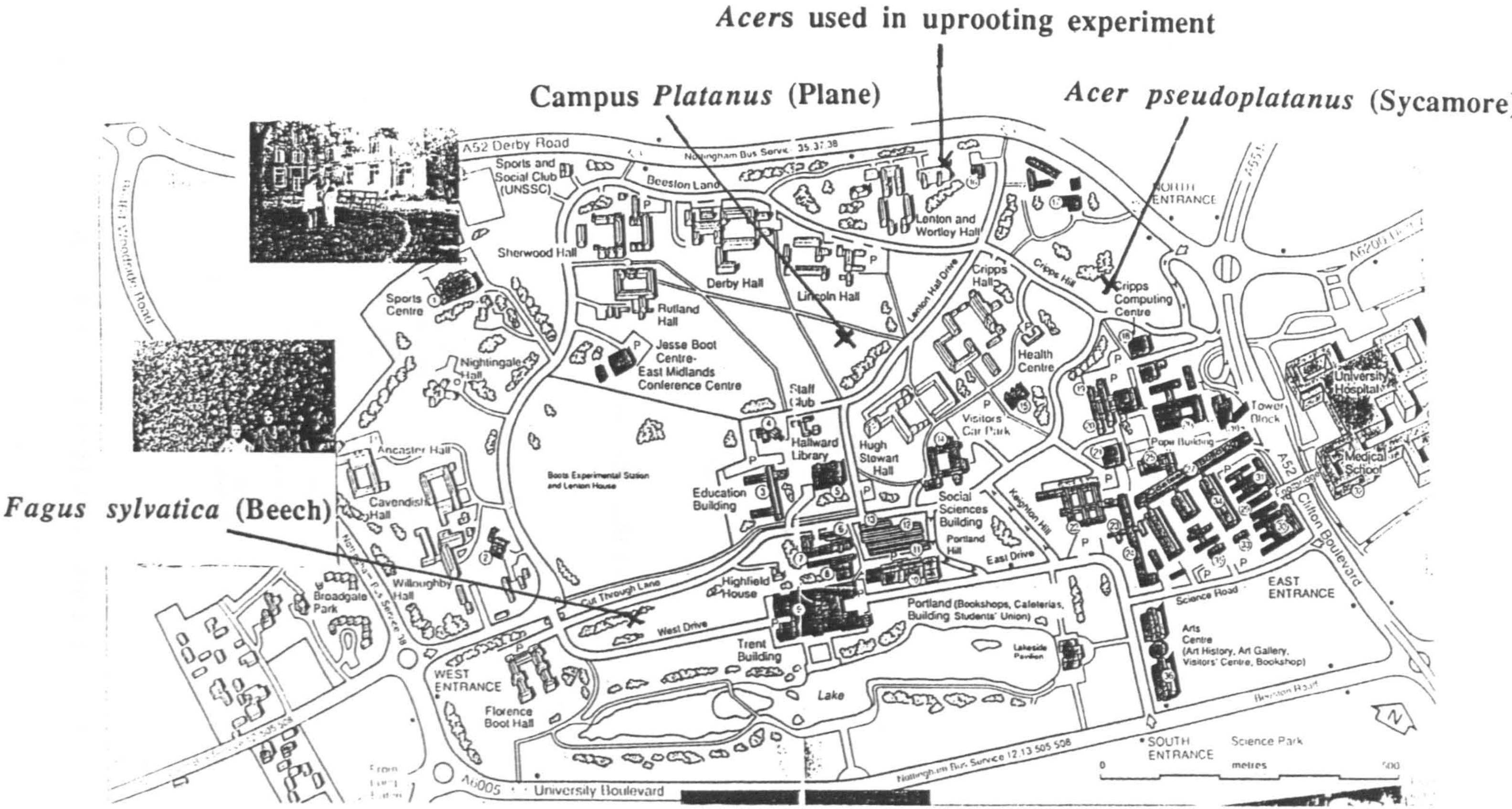


Figure 5.1 Map of University Campus showing experimental trees

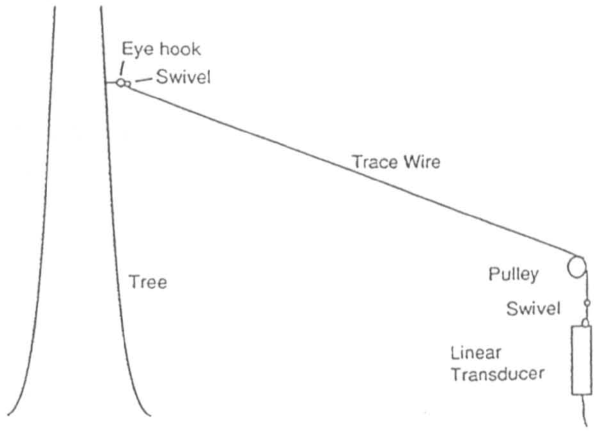


Figure 5.2 Trunk displacement apparatus

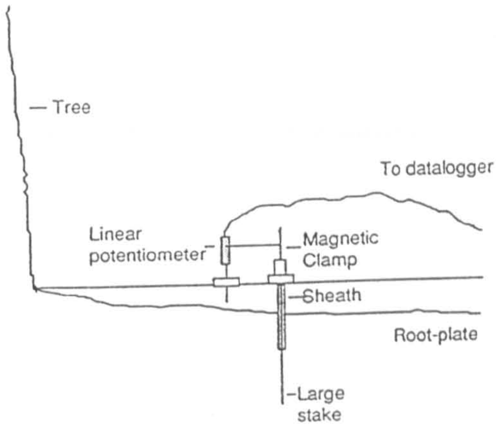


Figure 5.3 Root displacement apparatus

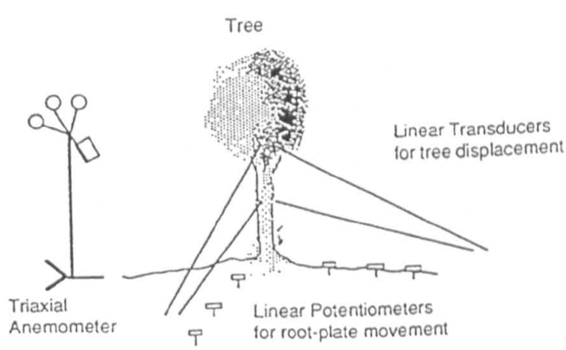


Figure 5.4 Layout of instruments in relation to trees

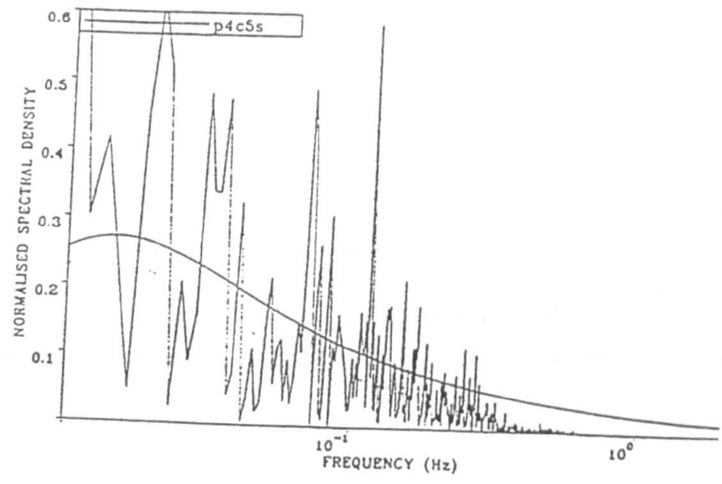


Figure 5.5 Typical wind power spectra diagram

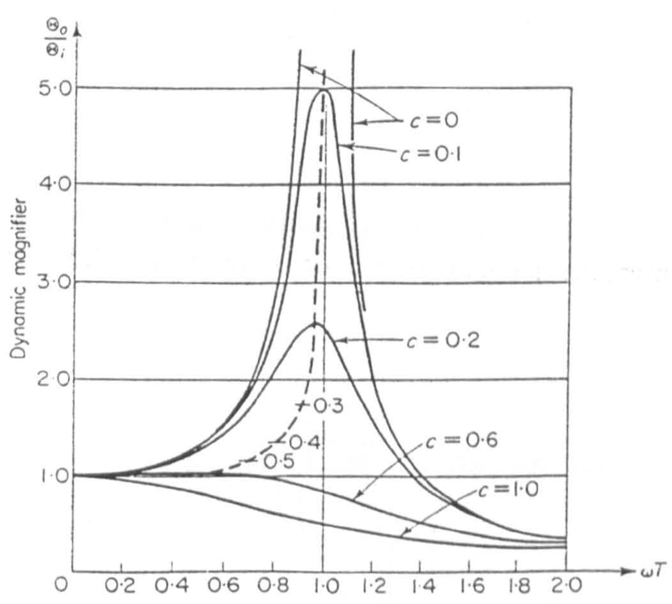


Figure 5.6 Graph from which to derive values of damping coefficient, (Prentis 1970)

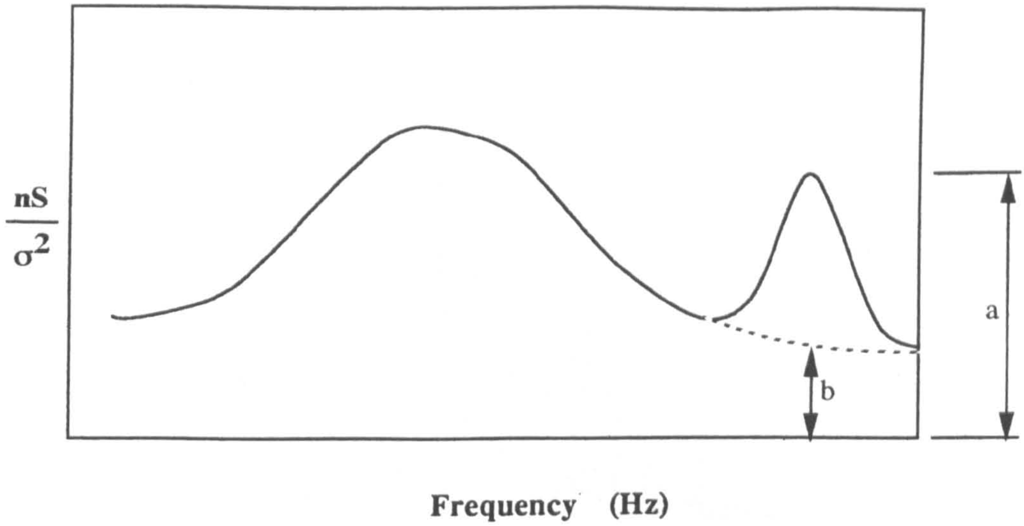


Figure 5.7 Sketch of wind speed and tree displacement spectra

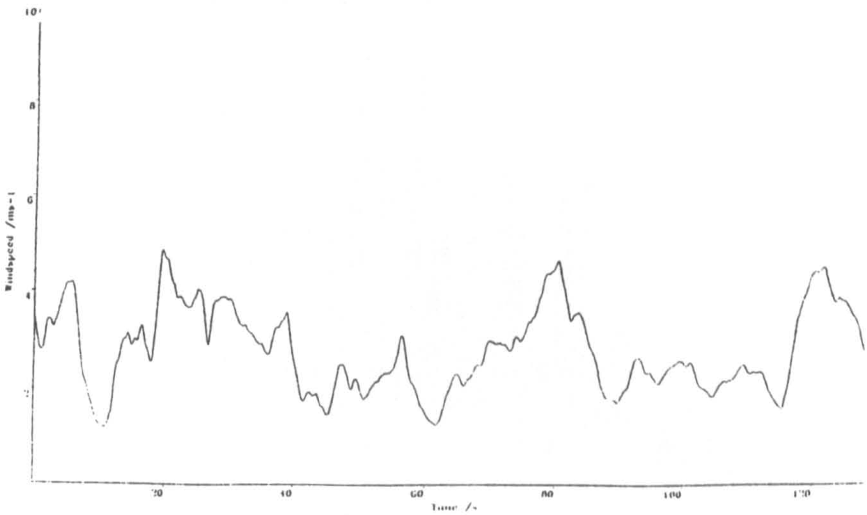


Figure 5.8 Acer - Wind speed time series

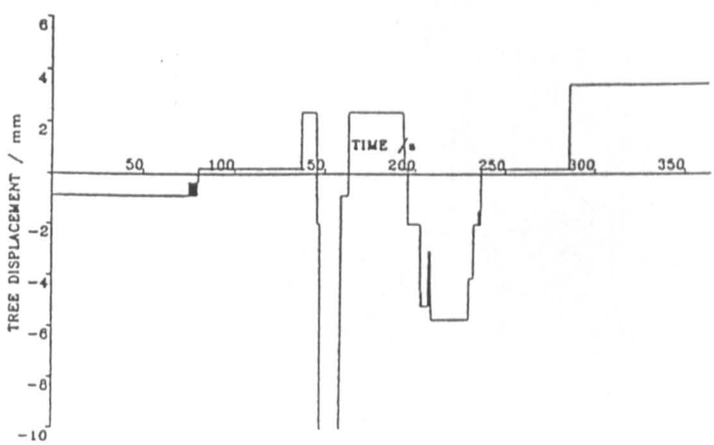
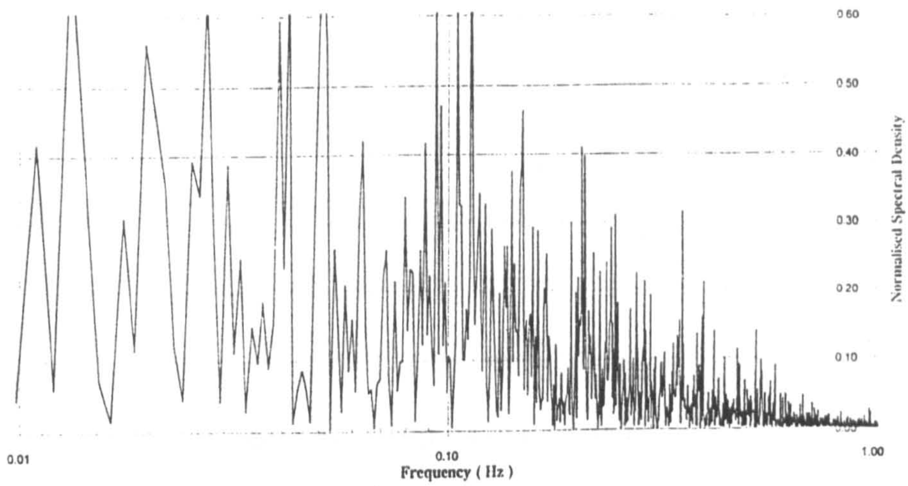
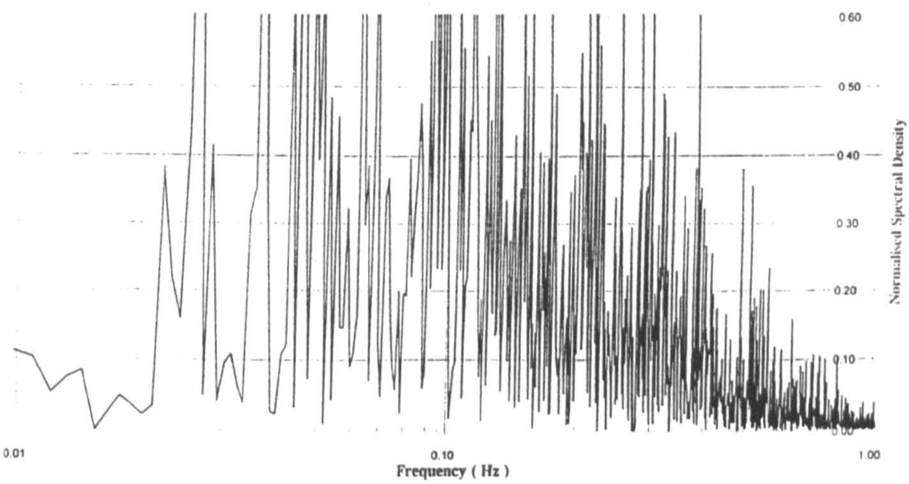


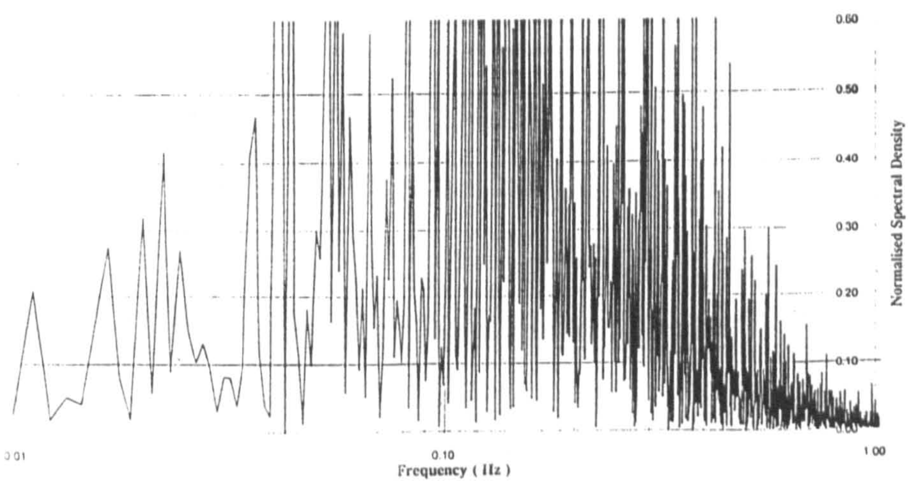
Figure 5.9 Acer - Tree displacement time series



a) Wind speed in the direction of the wind

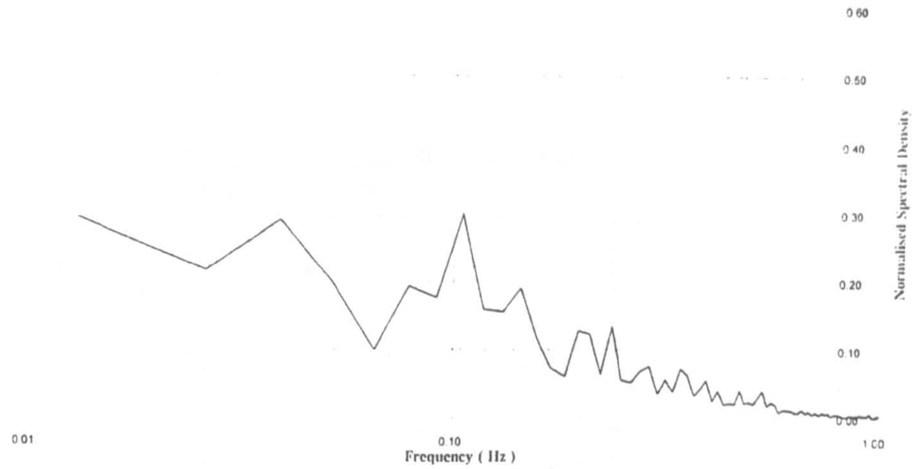


b) Wind speed horizotally at 90 degrees to the wind

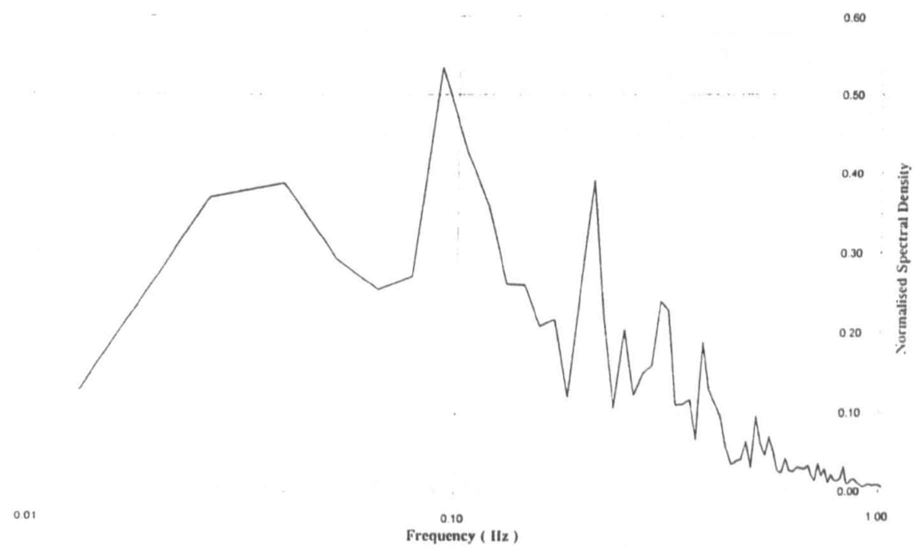


c) Wind speed vertically

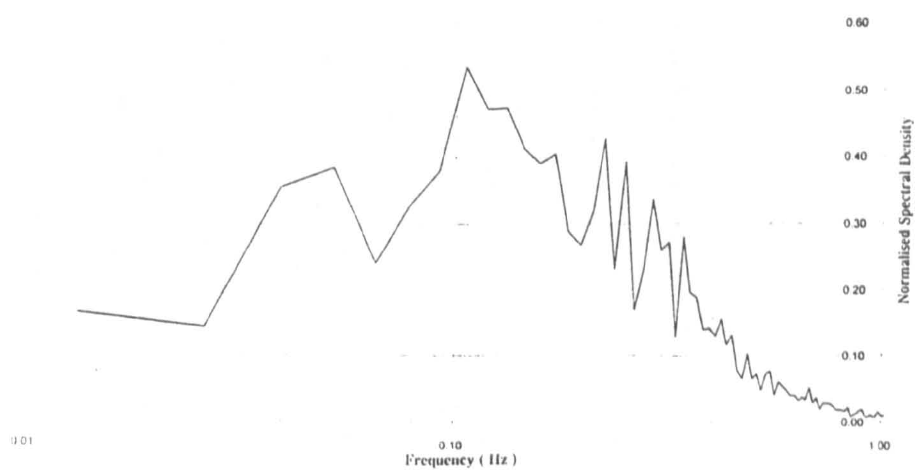
Figure 5.10 Wind spectra - in each wind direction



a) Wind speed in the direction of the wind

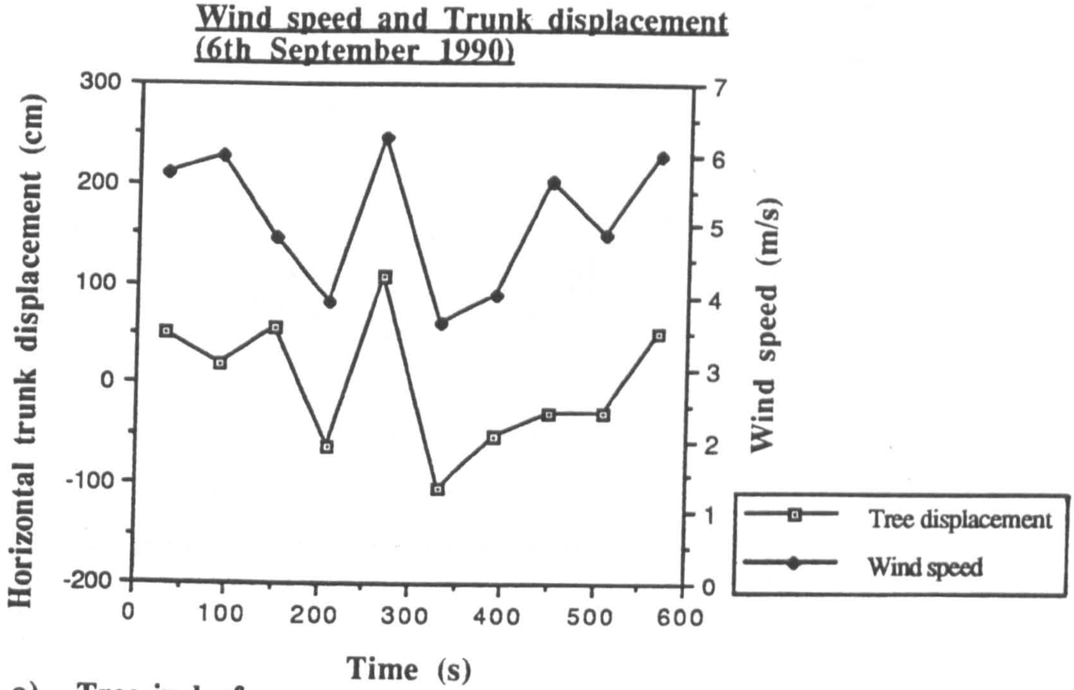


b) Wind speed horizotally at 90 degrees to the wind

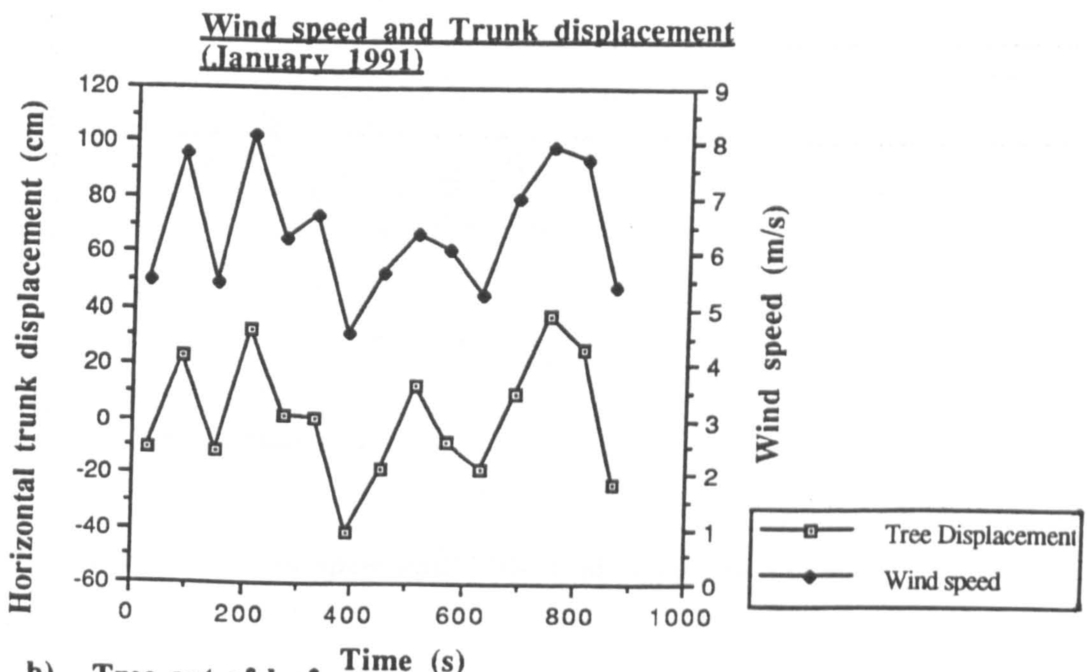


c) Wind speed vertically

Figure 5. 11 Wind spectra averaged

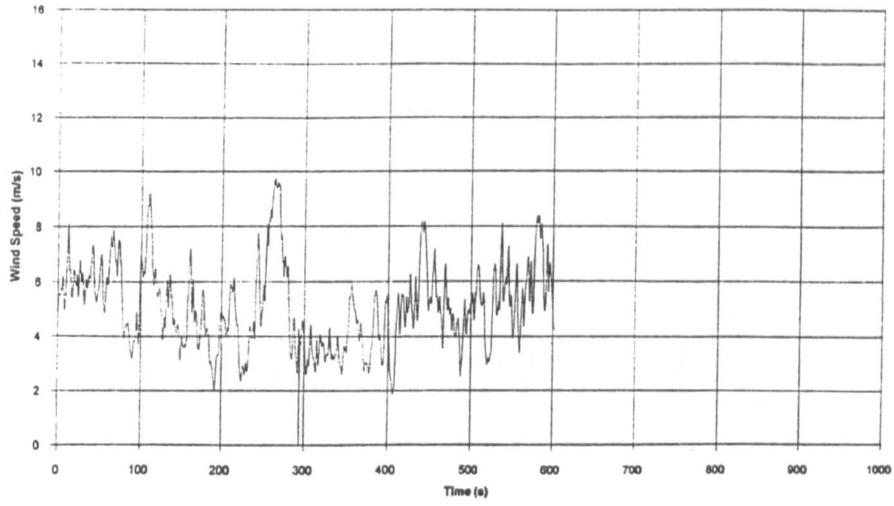


a) Tree in leaf

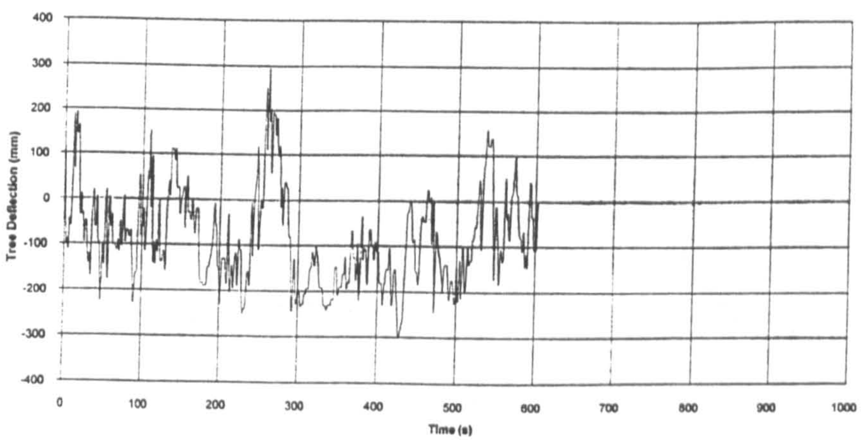


b) Tree out of leaf

Figure 5.12 Minute averages. Wind speed and trunk displacement

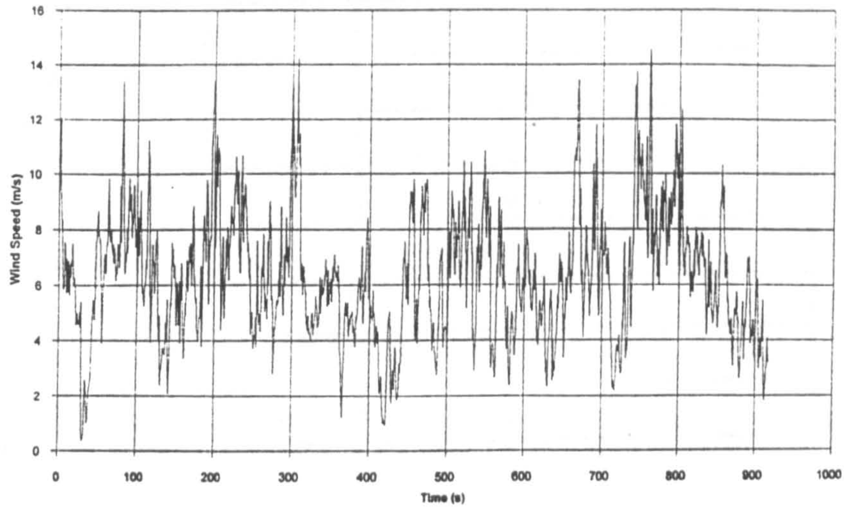


a) Wind speed

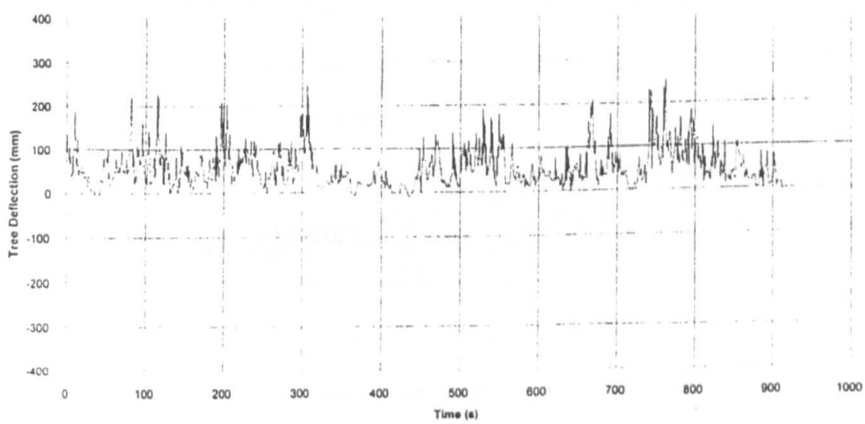


b) Trunk displacement

Figure 5.13 Wind speed and trunk displacement time series for tree in leaf

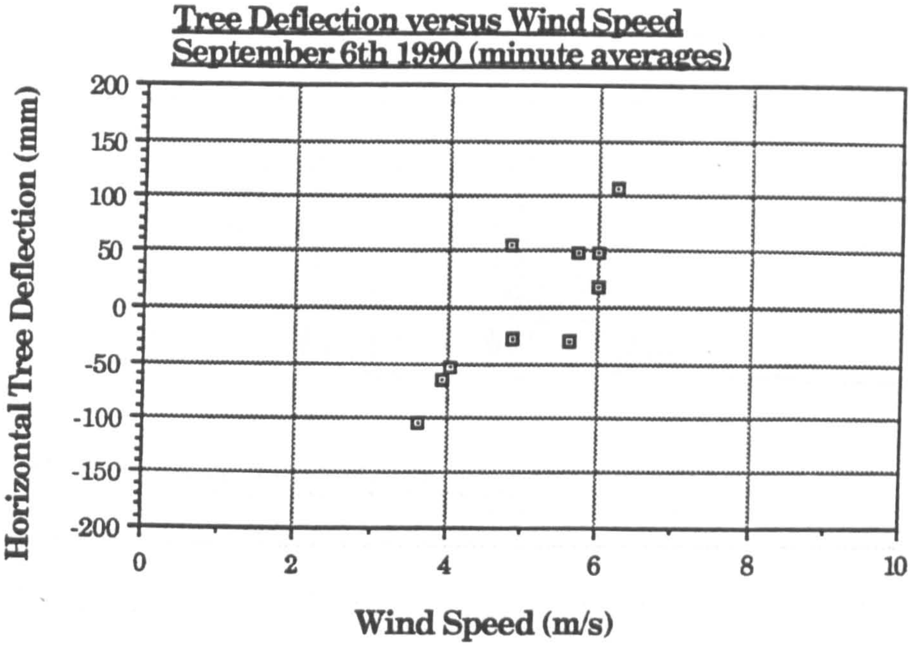


a) Wind speed

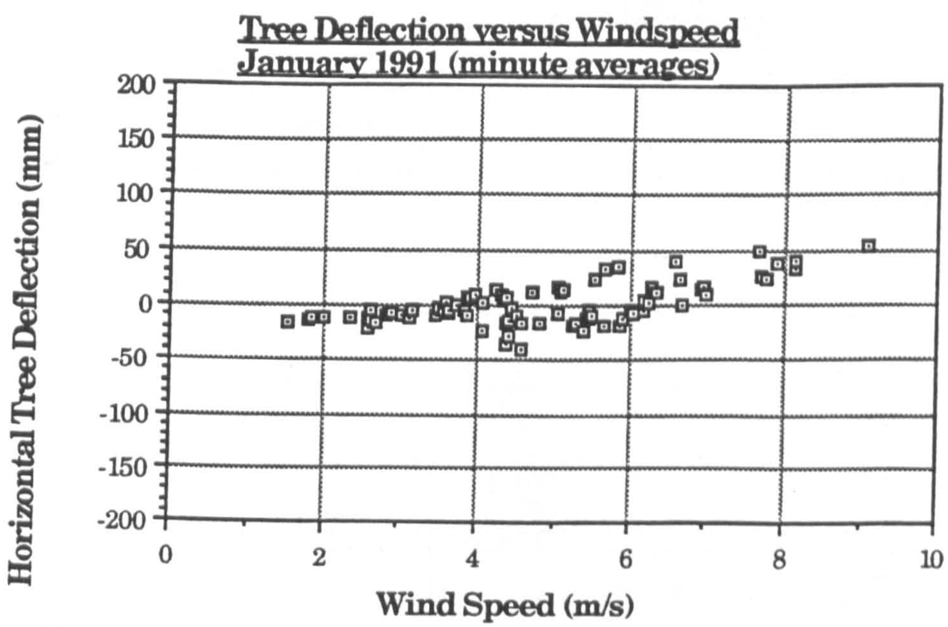


b) Trunk displacement

Figure 5.14 Wind speed and trunk displacement time series for tree out of leaf

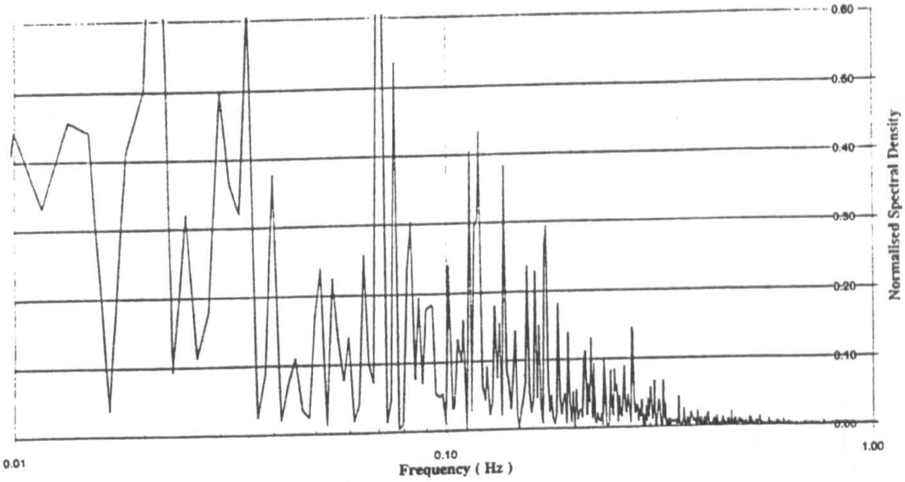


a) Tree in leaf

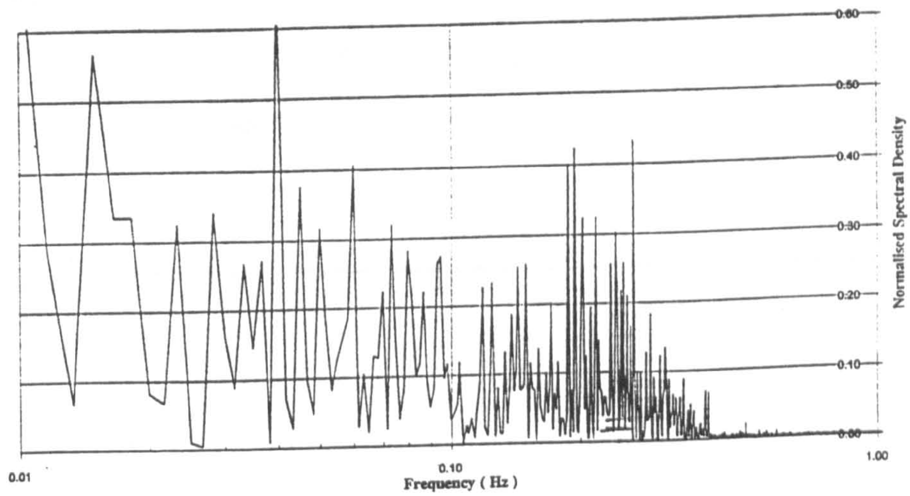


b) tree out of leaf

Figure 5. 15 Graphs of wind speed versus trunk displacement
In and out of leaf



a) Wind speed spectrum



b) Tree displacement spectrum

Figure 5. 16 Wind speed and trunk displacement spectra - tree in leaf

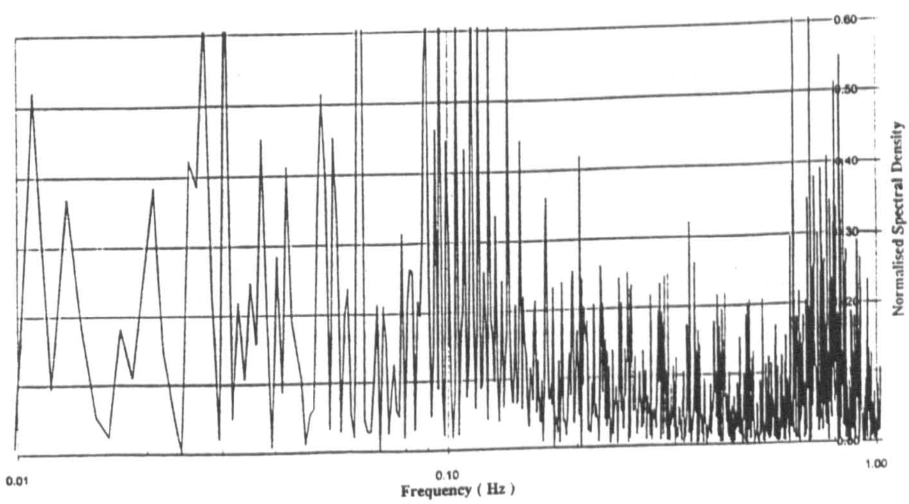
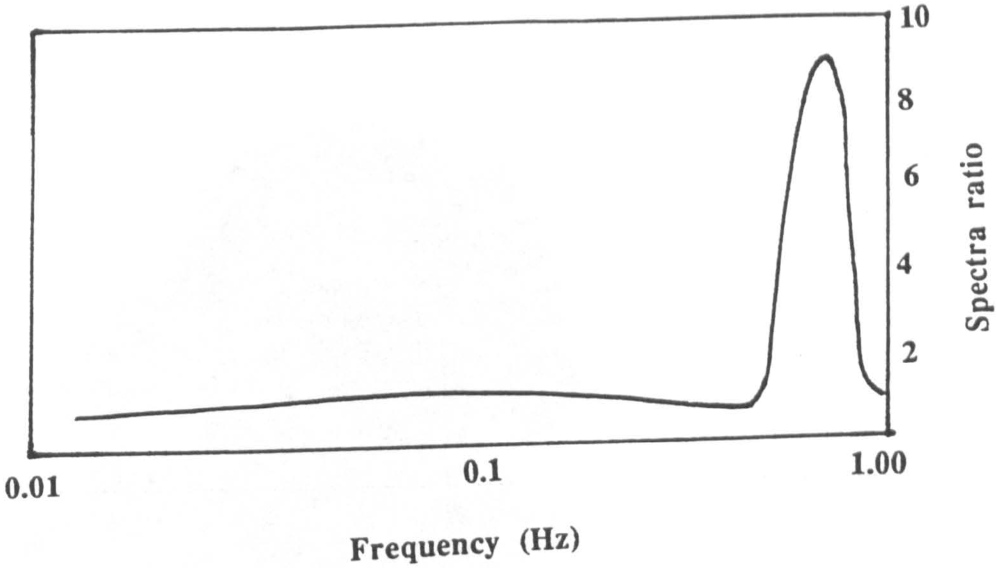
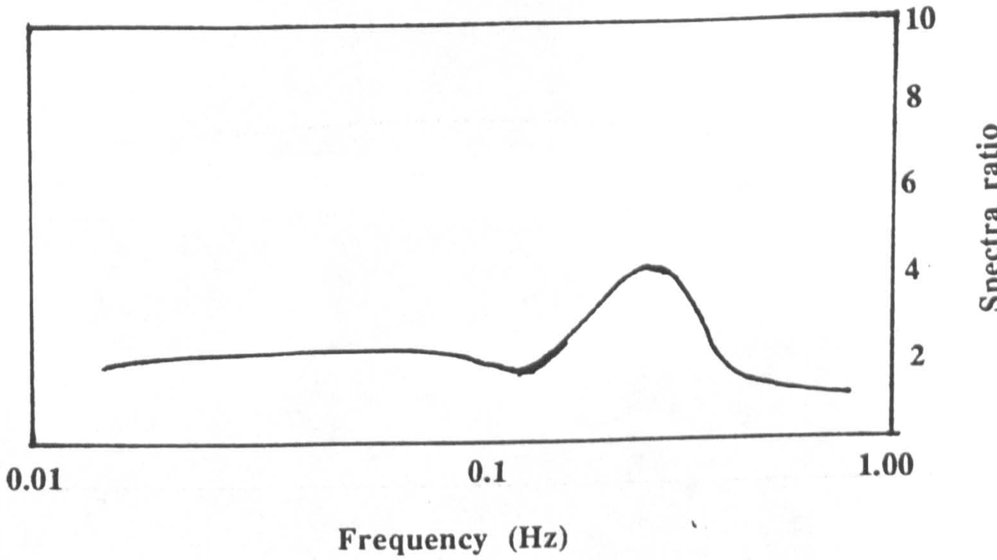


Figure 5. 17 Trunk displacement spectrum - tree out of leaf



a) Tree out of leaf



b) Tree in leaf

Figure 5.18 Admittance - in and out of leaf

Plate 5.1 - *Acer pseudoplatanus* selected for observation in the wind

Plate 5.2 - Wind fetch of *Acer pseudoplatanus*

Plate 5.3 - *Fagus sylvatica* selected for observation in the wind

Plate 5.4 - Wind fetch of *Fagus sylvatica*

Plate 5.5 - 'LEDA" anemometer positioned beside the *Platanus*

Plate 5.6 - *Platanus acerifolia* selected for observation in the wind

Plate 5.7 - Wind fetch of *Platanus acerifolia*

Chapter 6

Enforced tree oscillation

6.0 Introduction

The experiments described in Chapter 5 investigated the response of trees in windy conditions. One factor which could not be measured in those series of experiments however, was the force which the wind exerted on the tree, causing it to deflect. Controlled static loading of the tree could be monitored to produce load/ deflection curves. From this, and wind deflection data, it would be possible to make a reasonable estimate of the force on the tree and thus the drag coefficient (information currently only known for a number of coniferous species). Knowledge of the drag coefficient would increase the accuracy of being able to predict the response of trees in high winds.

Tree failure has been shown to be a dynamic process (Section 2.2). In the following series of experiments the tree was subjected to a slowly increasing force, then released instantaneously, and allowed to recover its resting position. All movements were monitored, and values for the frequency of oscillation and damping were calculated. These were compared with those gathered by monitoring the tree in the wind.

Two series of experiments were carried out. The first on the campus *Platanus* which was used in the wind monitoring experiments, and the second on eight trees in a site in Blidworth. The results of the campus *Platanus* could then be compared directly with the results of the wind deflection experiments (Section 5.5), with the tree in different states of crown cover, and values for the drag coefficients of the campus *Platanus* in and out of leaf could be derived. The Blidworth trees were not measured in the wind, but the results complement those of the campus *Platanus*.

The Blidworth trees were available for uprooting and the results of this process are discussed with additional uprooting experiments in the following chapter (Chapter 7).

6.1 The Experiment

6.1.1 Characteristics of the Trees

The campus *Platanus,* used in the wind observations (Chapter 5), was the first subject for forced oscillation. This tree was tested five times at three distinctly different times of the year. Testing occurred on the 11th December 1990, the 25th April 1991, the 22nd August 1991, the 11th December 1991 and the 28th April 1992. In August the tree was in full leaf, in December it had no leaves and in April the leaves were on the point of emergence from the buds.

The second series of experiments involved eight trees of varying species, two *Platanus,* two *Acer saccharinum* (Silver maple) and four *Sorbus aria* (Whitebeam). These trees were located on a road side verge at a site in Blidworth (Plate 6.1), a small mining village in North Nottinghamshire (G.R. 4593 3561). Details of the tree species, heights, and trunk diameters are given in Table 6.1. The trees were monitored twice in the month of May in consecutive years 1991 and 1992, allowing comparison to be made with the campus *Platanus* when it was monitored in April.

6.1.2 Experimental procedure

A system was developed for small trees (less than 10 m high), to cause horizontal deflection of the trunk, then at a selected point, allow almost instantaneously release, initiating trunk oscillations. A 0.25 pulley system was used, pulling against either a much larger tree (Plate 6.2), or a road vehicle in the case of the Blidworth tests. These were assumed to be absolutely static therefore not affecting the experimental results. Figure 6.1 shows the connection of the pulley with the tree, load cell and monitor, ropes and expendable rope strop. The exact location of the linear transducers and loading apparatus for each session are given in Appendix D.

The increasing load was monitored on a digital voltmeter at regular intervals of 0.12 mV, representing approximately 0.077 kN. (The force on the tree was known approximately at this stage, but the angle it was incident on the tree still had to be calculated and so the actual force varied slightly between trees and so is not given here.)

Problems were encountered in sustaining specific load levels, (the load slowly decreased). This was unavoidable, but the position of the tree was recorded after a 5 second period to allow for the delayed response and to keep the results consistent. At each load interval the tree deflection was monitored using the Campbell CR10 datalogger, in conjunction with linear transducers as used in earlier experiments (Section 5.1.2). Only one linear transducer was mounted on the trees at Blidworth, at a height of approximately 3.6 m. Ground movement was also monitored, again with the system described earlier (Section 5.1.2).

A clean cut was made through the expendable rope strop with a chisel and mallet (Plate 6.3). The strop and loading rope were then free to oscillate with the tree. Their interaction and damping affect were assumed to be negligible. The trunk and ground movement were recorded at a rate of 4 Hz.

The loading and release of the campus *Platanus* was repeated more than once on each testing day. This enabled the lateral tree movement (90° to the direction of loading) to be assessed. Either the high or low linear transducer was moved to a position on the trunk at 90° from its former position before loading was reapplied.

The *Platanus* was always deflected in the same direction (Plate 6.4), which also corresponded to the deflection caused by the prevailing wind. The loading of the Blidworth trees was not so consistent due to their roadside location and related practical difficulties, but the direction of deflection was always recorded.

On the days when the forced oscillation took place the wind speed was minimal, with the exception of the second day of testing at Blidworth when a light gusting breeze began towards the end of the day.

6.2 The analysis

A load/ deflection curve was produced for each loading for each testing, by plotting the amount of tree deflection at each load interval against the actual force incident on the tree. The slope of this curve is the displacement force ratio of the tree.

A time series was plotted to show the trunk oscillation after each release. From this graph both the natural frequency of oscillation and the damping coefficient were determined.

The natural frequency was determined by dividing a selected number of peaks by the time over which they occurred.

The damping coefficient determination involved the decay of the amplitude of tree deflection. Figure 6.2 shows a theoretical time series of the enforced tree oscillation. Using the following equation (equation 6.1), and substituting experimental results, the damping ratio was calculated.

$$c = -\frac{\pi}{\delta} + \sqrt{\left(\frac{\pi}{\delta}\right)^2 + 1} \qquad 6.1$$

where $\delta = \ln\left(\frac{\theta_i}{\theta_{i-1}}\right)$, the logarithmic decrement (Prentis, 1970)

Ground movement was also plotted as a time series wherever significant movement was monitored.

6.3 Results of the campus *Platanus*

6.3.1 Load deflection curves

Load deflection curves for each recording session are shown in Figure 6.3. These curves represent the average curve of all repetitions of the winching on each particular session, though there was little variation between repetitions.

In each case the tree was observed to deflect with a roughly linear relationship with applied load. The load/ deflection ratios (or stiffness) are given in Table 6.2. There was little difference in the variation of slope with repetitive loading. The stiffness did not appear to be related to the time of year and leaf cover of the tree.

The linear transducer fixed at the lower point on the trunk again produced almost linear deflection curves but showing smaller deflection at each reading as would be expected. The forced oscillation results too are calculated on data from the higher fixed linear transducer. Again the lower transducers gave similar results, but of lower amplitude.

6.3.2 Time series

The time series graphs showed there to be a marked difference in the tree's response on releasing according to the time of year. The results from December 1990 and 1991, and April 1991 and 1992, when the tree had no leaves, showed a similar response (Fig. 6.4). The tree was observed to oscillate approximately 12 times with diminishing amplitude before coming to rest. The repeatability of the results on each recording day was again very good, and there was in fact little difference between the times series of these four recording days. In August 1991 however, when the tree was in full leaf, only 2 or 3 oscillations were observed (Fig. 6.5).

The dramatic reduction in number of oscillations undergone by the tree before reaching its resting position whilst the tree was in leaf indicates that the leaves cause much greater damping than that which occurred without the leaves present. Damping coefficients determined from the respective time series confirmed this to be the case (Table 6.3). The damping ratio was found on average to be 0.423 when leaves were present but 0.052 with leaves absent.

The frequencies of oscillation of the tree are also given in Table 6.3, and again a marked difference was observed between the tree in and out of leaf. The frequency was seen to vary only slightly, from 0.75 Hz to 0.87 Hz, when the tree had no leaves. In August 1991 however, whilst the tree was in leaf, the frequency was 0.42 Hz, approximately half that of when it had no leaves on.

6.3.3 Lateral Oscillation

Lateral movement was monitored on all but the first recording session. Force displacement curves show the ratio to be much smaller (Table 6.4), of the order of ten less than in the direction of loading. Negative ratios were calculated for the tree on the occasions were the low linear transducer was used to record the lateral degree oscillation. (Fig. 6.6).

On the release of the tree the time series traced showed a frequency equal to that of the tree movement in line with the applied load (Table 6.4). The actual trace however varied. The traces for the tree without leaves showed an initial lessening of amplitude, which then increased after approximately 5 seconds, to peak at approximately 8 seconds before it died (Fig. 6.7). The trace however was of much smaller amplitude than in the direction of loading, of the order of tens of millimetres as opposed to hundreds of millimetres. This is illustrated in Figure 6.8, which shows the tree movement in the loading direction plotted against the corresponding lateral trunk motion. The recording in August 1991 was heavily damped and closely reflected the trace in the loading plane (Fig. 6.5).

6.3.4 Ground movement

During the slow winching of the tree, ground movement, (which was usually very small) was monitored. Movement was recorded most frequently by the linear potentiometer which was positioned half a metre in front of the tree (from the direction of the load application). Movement was of the range of 0.05 mm and this was in an upwards direction. The linear potentiometers 'pot 1' and 'pot 3', positioned one metre either side of the tree recorded negligible movement during winching.

On the release of the tree, the ground was observed to oscillate in a similar manner to the tree trunk (Fig. 6.9), though movement was only detected by 'pot 2'. Far fewer oscillations were observed in the August data, when the tree had leaves, than on other days (Fig. 6.10), though April 1992 also recorded surprisingly low results. The number of oscillations of the ground was however fewer than for the trunk. This reduction in oscillation number could be due to the increased damping of the ground system, or simply due to the difficulty in monitoring such small sizes of movement. Table 6.5 gives the average number of oscillations measured and the maximum displacement of the linear potentiometer for any one release on each experimental testing day.

6.4 Results of the Blidworth trees

6.4.1 Load deflection curve

The trees at Blidworth again produced almost linear load deflection curves (Fig. 6.11). The displacement force ratios (Table 6.6) were compared with the results from both the high and low linear transducers of the campus *Platanus*. (Table 6.2). They were found to be closer to the higher linear transducer results than the low, and in most cases were greater, though of the same order. Although the heights at which the wires were attached to the Blidworth trees were approximately equal to the height of the lower linear transducer on the campus *Platanus*, as a ratio of the attachment height and tree height the Blidworth trees were measured at a height closer to the campus *Platanus* when it was measured with the high linear transducer.

Four of the Blidworth trees were tested twice on following years. The displacement force ratios were found to be lower in the second year of testing, showing less deflection for the same applied loads. The displacement force ratio decreased with increasing trunk diameter (Fig. 6.12). An increase of 1- 3 cm was recorded in the circumference of the base of the four trees tested in consecutive years (Table 6.1), but whether one years growth could account for such a change in displacement force ratio was questioned. (Trunk diameter at breast height is thought to be a more reliable parameter as it reduces the abnormalities of uneven growth often present at the base of the tree due to root formation. Unfortunately however this parameter was not measured in 1992, so the basal diameters were compared.) A similar observation was noted in the displacement force ratios calculated for the campus *Platanus* in subsequent December testings, though there was no noticeable increase in trunk diameter (Table 6.7). Little explanation could be found, other than speculation about ground condition, air temperature and humidity.

There appeared to be few apparent differences between the different tree species, though it was difficult to determine with such a small number of samples, particularly when size appears also to be an important factor. This being said, it may be that the *Sorbus aria* had a higher displacement force ratio than the *Acer saccharinum.*

6.4.2 Time series

The time series showed similar traces to the campus *Platanus*. Frequencies and damping ratios determined from these traces are given in Table 6.8 (Table 6.3 for the Campus *Platanus*). The frequencies ranged from 0.59 Hz to 1.08 Hz. The two *Acers* monitored produced the higher frequencies, but the other trees had natural frequencies close to that of the campus *Platanus* whilst it was out of leaf. The damping ratios were also similar (0.044 to 0.110), with the exception of two *Sorbus aria* trees which had significantly higher damping ratios. It was noted however that these two trees had substantial leaf emergence and their damping ratios (0.192 and 0.300), were much closer to the *Platanus* (0.423) when it was in leaf.

6.4.3 Ground movement

Ground movement was recorded on both of the linear potentiometers used for each tree, one on either side, with the exception of one *Sorbus aria*, where only one was used due to locating difficulties. The potentiometers were situated closer to the tree trunks (18 - 25 cm) than they were for the campus *Platanus*. This was as a consequence of the small movement registered on the campus *Platanus*, and also because of the small tree pits (1 m^2) in which these street tress had been planted. Beyond the bounds of the tree pits, the ground comprised of compressed soil and gravel, which was impenetrable to the monitoring apparatus. It was also suspected that there would be little root growth beyond the bounds of the pit.

Ground movement was observed in 1992 to range from a depression of 0.4 mm to a rise of 3.5 mm, though only on two occasions did it rise to above 1 mm.

These values were far greater than those observed for the campus *Platanus* (0.05 mm). This could be due to the closer placement of the linear potentiometers, or due to the soil type and tree establishment. The *Platanus* had the superior conditions, planted in a good brown earth, without a marked difference in conditions outside the excavated soil pit. The soil in the Blidworth tree pits was of a very sandy composition with a relatively hostile environment beyond the bounds of the tree pit. A sandy soil would allow more movement than a good brown earth. The Blidworth trees were planted as standards, of approximately 40 cm girth, in 1984. This compared with the campus *Platanus* which was planted as a 5 year old tree, 13 years ago. The campus *Platanus* has therefore had longer to establish itself. One further factor is the quality of the actual planting technique used and how much care was taken not to damage roots or to jeopardise good root establishment.

Load/ displacement curves (Figs. 6.13 and 6.14) showed a greater increase in ground displacement with increasing loading. Below a load of 0.5 kN there was very little movement observed at all. The greatest values of displacement were found on the side of the tree away from the direction of loading. However for each tree the displacement was not always found to be greatest on the side of the tree away from the direction of pulling. The ground on the loading side of the tree was sometimes seen to depress. This was expected due to the turning moments of the load applied to the trunk. Movement must also have occurred horizontally towards the load, causing the soil to rise on that side of the tree. On occasions this appeared to be greater than the depression expected due to the turning moment. This movement may also have caused slight downward movement of the soil on the opposite side of the tree, but this never appeared greater than the lifting of the root-plate due to the turning moment.

The ground displacements of the trees tested in both years showed the ground to reflect the movement of the trunk, in that greater movement was observed in 1991 than in 1992. Figure 6.15 shows the ground movement for the trees in 1991, with a maximum movement of over 30 mm. Indeed it was probably this increased ground movement which allowed increased trunk movement in 1991. This was concluded as although the displacement/ force ratios showed a decrease with increasing trunk diameter and the trees grew larger before the second testing, it was thought that the growth was not sufficient to lower the displacement/ force ratio by such a great extent. A decrease in the stability of the roots, perhaps due to varying ground conditions appeared a more viable explanation.

No apparent differences were found between the load/ displacement response of each species tested.

On the release of the tree ground oscillation was recorded. There were however rarely more than two oscillations, so damping coefficients and frequencies were not determined.

6.5 Discussion of results and determination of drag coefficients

The results gained for the campus *Platanus* were to an large extent verified by those of the Blidworth trees. Some differences were recorded, particularly in the degree of ground movement, but it was felt that the majority of differences were adequately explained and/ or justified. The results of the Blidworth trees will be further discussed when their subsequent uprooting is described (Chapter 7). The results of the campus *Platanus* however must be compared with the results generated from the monitoring the tree's response in the wind.

Values of the tree's natural frequency of oscillation and damping ratios calculated for both the forced oscillation and the wind monitoring experiments showed very good agreement for the tree when it was both in and out of leaf (Tables 5.5 and 6.3). This showed the results to be compatible, and increased the confidence in the determination of drag coefficients that follows in this section. The damping ratio increased with the tree in leaf and the natural frequency decreased. Attempts were made by Roodbaraky et al (1994) to explain the changing natural frequency. As there was little variation in the trunk stiffness with season, the change in natural frequency was attributed solely to the changing mass of the tree's crown with and without leaves. The results suggested a doubling or trebling of the trees' mass with the growth of leaves which seems rather large. It is likely that more factors are involved in the change in natural frequency and more research in this area is recommended.

The drag coefficients were calculated according to the following equation:-

$$C_{DR} = D/0.5\ \rho A V^2 (V_R/V)^{(2-m)} \qquad 6.2$$

where **D** is the aerodynamic drag force, ρ is the density of air (1.2 kgm^{-3}), **A** is a reference area (taken as 10 m^2), **V** is the wind velocity and **V_R** is a reference wind velocity (10 ms^{-1}). The symbol 'm' represents 1 or 2 if the relationship of the tree displacement is assumed to vary linearly with the wind velocity or with the velocity squared respectively (Section 5.5.3.1). For m = 1 the above equation can be written:-

$$C_{DR} = (D/x)\,(x/V)\,/\,(0.5\rho A V_R) \qquad 6.3$$

and for m = 2, the following equation can be written:-

$$C_{DR} = (D/x)\,(x/V^2)/\,(0.5\rho A). \qquad 6.4$$

The D/x ratios can be found from the results of Figure 5.20 and the ratios x/V^2 and x/V in these equations are given by the values of the parameter b in the Table 5.4. Thus drag coefficients may be found from the force/ deflection and wind speed/ deflection characteristics. Drag coefficients calculated for both m = 1 and m = 2 (Roodbaraky et al 1994) are given in Table 6.9.

The tree with leaves was found to have a far greater drag coefficient than when it had no leaves. This was irrespective of which value was used for 'm'. Indeed little difference was observed in the drag coefficient values calculated for m = 1 and m = 2. Mayhead's results (1973a) however, suggest the drag coefficient to be related to wind speed squared.

The drag coefficients 0.14 - 0.36 given by Mayhead (1973a), for a selection of conifers, were derived for the trees for a wind speed of 30.5 ms^{-1} (at such wind speed the drag coefficient was found not to vary significantly with wind speed). These results were however, extrapolated from measurements taken in wind speeds of 9 ms^{-1} to 26 ms^{-1}. The drag coefficients of the Campus *Platanus* were calculated using data collected with a mean wind speed of 5.8 ms^{-1}. These can therefore be compared with curves plotted by Mayhead (1973a), with reasonable confidence.

The drag coefficient calculated for the *Platanus* (Table 6.9) in full leaf was 0.888 or 0.841 depending on whether the tree displacement is assumed to vary with wind speed or wind speed squared respectively. Both of these values lie at the higher end of the drag coefficient range found for the conifers (Fig. 6.16). The *Platanus*, while without leaves however, has a drag coefficient of 0.193 or 0.205 respectively, which is considerably below that of the conifers.

6.6 Conclusions

a) The displacement/ load ratio does not vary greatly between seasons. The results indicated however, that this ratio decreases as the trunk diameter increases, but more experimentation would be required to confirm this.

b) A tree has a lower natural frequency of oscillation when it is in leaf.

c) The damping ratio is higher for a tree in leaf.

d) The hypothesis proposed by Fraser (1962) and Mayhead (1973a), of the drag being proportional to velocity, as opposed to velocity squared was not confirmed.

e) The drag coefficient of a tree is much higher when it is in leaf, than when it has no leaves.

f) The drag coefficient of the *Platanus* whilst in full leaf was within the range calculated by Mayhead (1973a). This suggests that broadleaf trees have similar drag coefficients to conifers.

Tables : Chapter 6

Tree	Height (m)	Trunk circumference at base (cm) May 1991	Trunk circumference at base (cm) May 1992	Trunk circumference at Breast height, 1.3 m May 1992 (cm)	Location in Dale Lane outside house no.
Platanus 1	7.13	44	45	34	119
Acer saccharinum 1	7.37	48	51	38	119
Sorbus aria 1	5.07	35	36	28	71
Sorbus aria 2	9.82	34	37	28	69
Platanus 2	8.20		49	40	1
Acer saccharinum 2	7.45	-	60	43	125
Sorbus aria 3	8.40	-	48	32	91
Sorbus aria 4	5.22	-	34	26	3

Table 6.1 Characteristics of the Blidworth trees

Date	Displacement force ratio (m/N)	Leafiness of crown
Dec 1990	$6.00 * 10^{-4}$	none
April 1991	$6.90 * 10^{-4}$	none
Aug 1991	$5.33 * 10^{-4}$	full
Dec 1991	$2.13 * 10^{-4}$	none
April 1992	$4.00 * 10^{-4}$	none

Table 6.2 Displacement/ force ratios for the campus *Platanus*

Date	Natural frequency (Hz)	Damping ratio	Leafiness of tree
Dec 1990	0.80	0.064	none
April 1991	0.75	0.043	none
Aug 1991	0.42	0.423	full
Dec 1991	0.87	0.045	none
April 1992	0.75	0.056	none

Table 6.3 Natural frequency and damping ratio for the campus *Platanus*, calculated from winching and release experiments

	Load deflection ratio (m/N)	Position of linear transducer	Frequency of Oscillation (Hz)
April 1991	$- 1.64 * 10^{-5}$	Low	0.85
August 1991	$1.47 * 10^{-4}$	High	0.45
December 1991	$5.67 * 10^{-5}$	High	0.9
April 1992	$- 1.60 * 10^{-5}$	Low	0.75

Table 6.4 Parameters determined from lateral tree deflection

	December 1990	April 1991	August 1991	December 1991	April 1992
Maximum ground movement (mm)	0.09	0.11	0.02	0.06	0.03
Average number of oscillations	7	6	1	5	2

Table 6.5 Ground movement measured on linear potentiometer 2 after winch and release tests.

Tree	Displacement force ratio (m/N) May 1991	Displacement force ratio (m/N) May 1992
Platanus 1	$8.69 * 10^{-4}$	$7.07 * 10^{-4}$
Acer saccharinum 1	$5.22 * 10^{-4}$	$2.73 * 10^{-4}$
Sorbus aria 1	$13.8 * 10^{-4}$	$6.90 * 10^{-4}$
Sorbus aria 2	$11.8 * 10^{-4}$	$9.81 * 10^{-4}$
Platanus 2	-	$4.09 * 10^{-4}$
Acer saccharinum 2	-	$4.87 * 10^{-4}$
Sorbus aria 3	-	$6.34 * 10^{-4}$
Sorbus aria 4	-	$5.82 * 10^{-4}$

Table 6.6 Variation of displacement force ratio for Blidworth trees

Date	Trunk circumference at breast height ,1.3m (cm)
6th Sept 1990	-
19th Sept 1990	48
11th Dec 1990	-
5th Jan 1991	-
25th April 1991	-
22nd Aug 1991	53
24th Sept 1991	53
11th Dec 1991	52
10th March 1992	52
25th April 1992	53

Table 6.7 Variation of trunk circumference of campus *Platanus*

Tree	Natural frequency (Hz)		Damping ratio	
	May 1991	May 1992	May 1991	May 1992
Platanus 1	0.81	0.76	0.044	0.063
Acer saccharinum 1	0.73	1.08	0.056	0.110
Sorbus aria 1	0.75	0.71	0.096	0.110
Sorbus aria 2	0.66	0.59	0.073	0.064
Platanus 2	-	0.78	-	0.110
Acer saccharinum 2	-	1.03	-	0.081
Sorbus aria 3	-	0.63	-	0.192
Sorbus aria 4	-	0.75	-	0.300

Table 6.8 Natural frequencies and damping ratios of the Blidworth trees

Date of winch / release test	Date of wind monitoring	Drag coefficient (m = 1)	Drag coefficient (m = 2)	Leafiness of tree
11th Dec 1990	15th Jan 1991	0.193	0.205	none
22nd Aug 1991	24th Sept 1991	0.888	0.841	full

Table 6.9 Drag coefficient of the campus *Platanus*, in and out of leaf

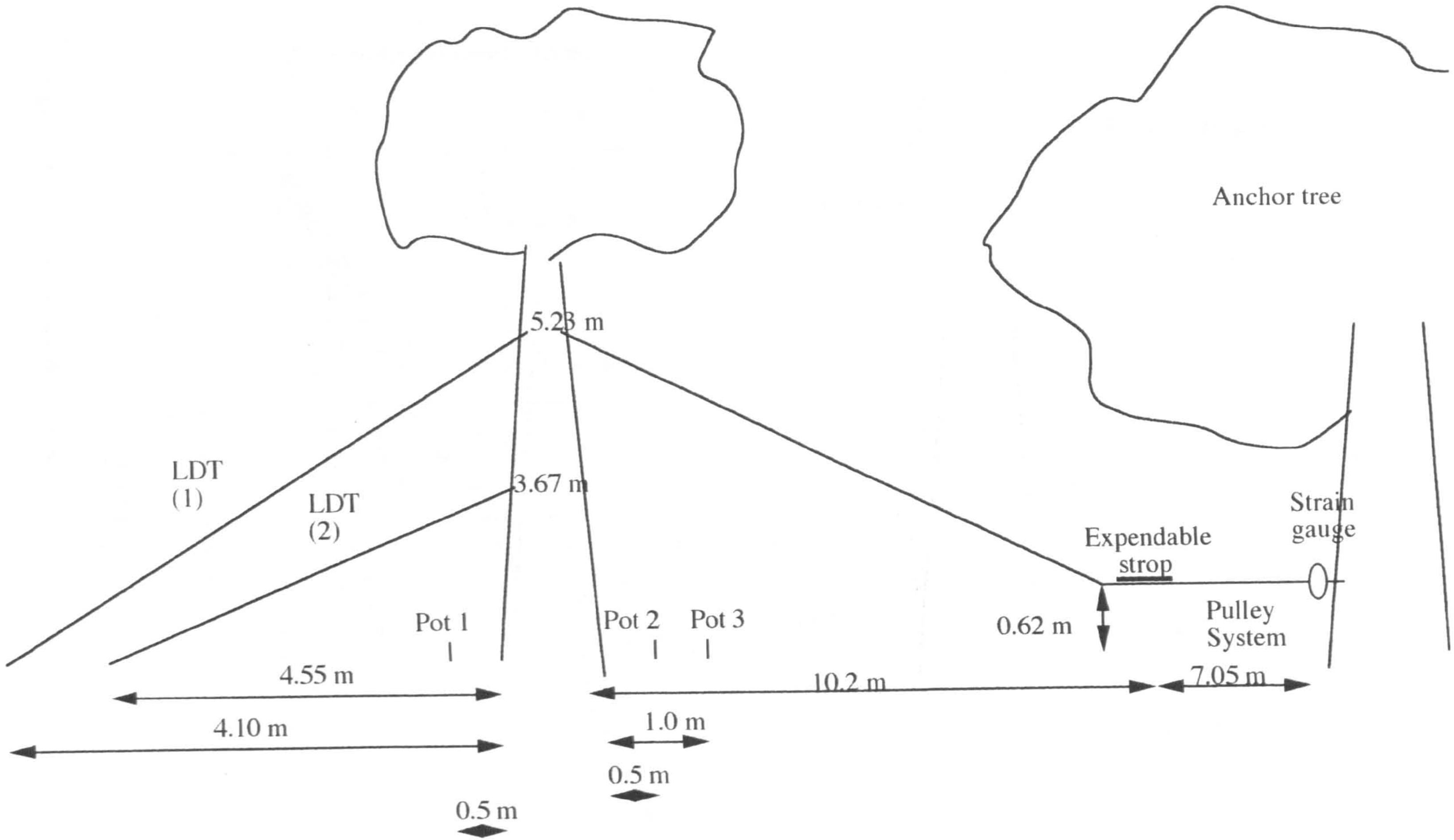


Figure 6.1 Apparatus for loading and release experiments
nb. for the varying distances etc. of each session see Appendix D

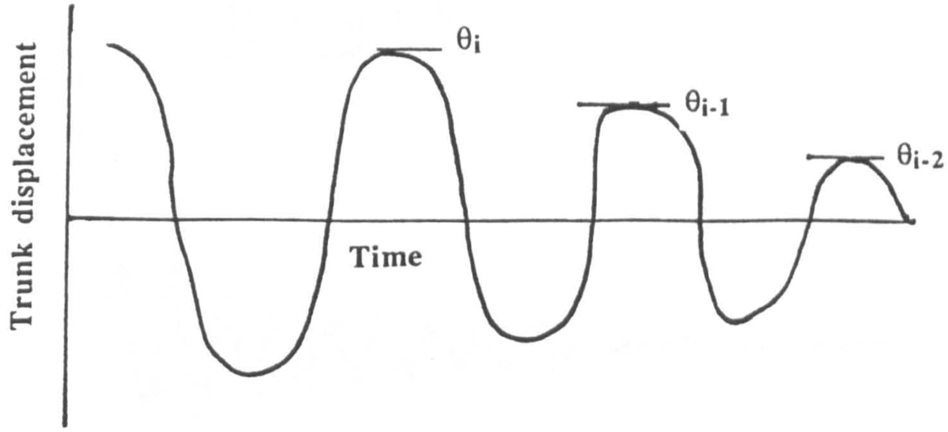


Figure 6.2 Theoretical time series of a displaced tree

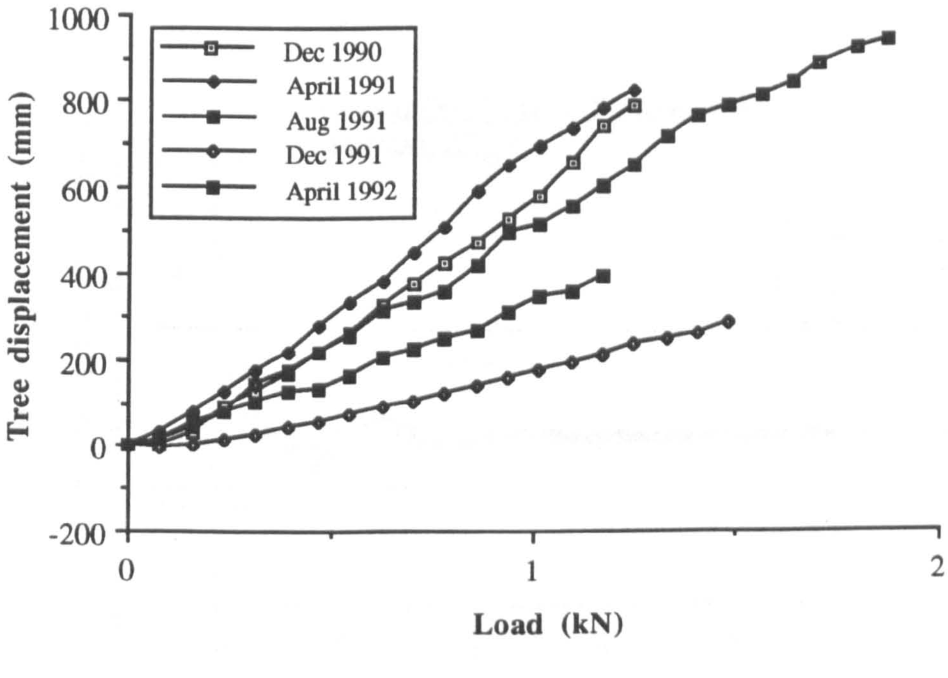


Figure 6.3 Load displacement curve for Platanus

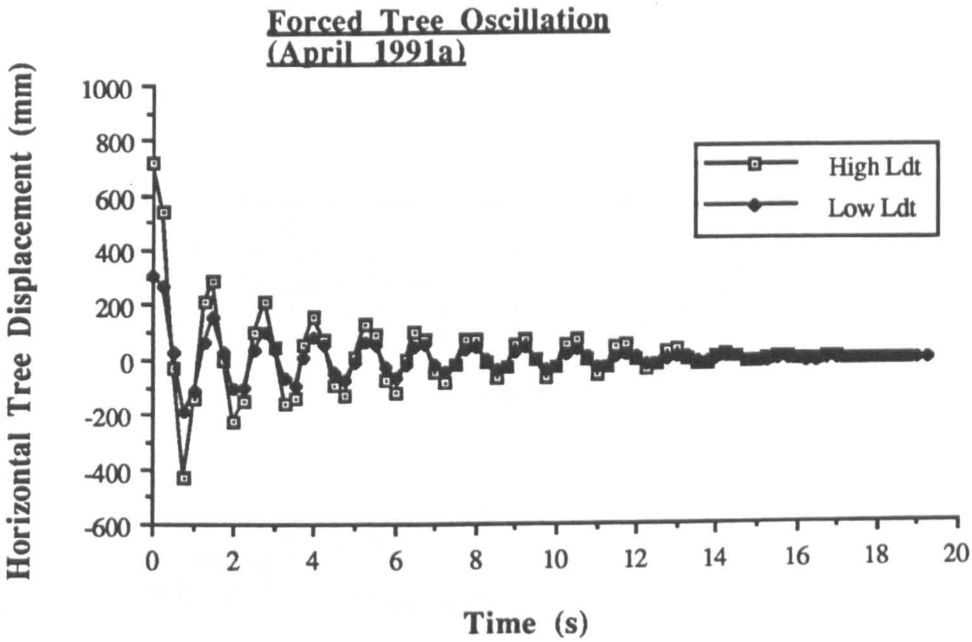


Figure 6.4 Trunk displacement time series - tree out of leaf

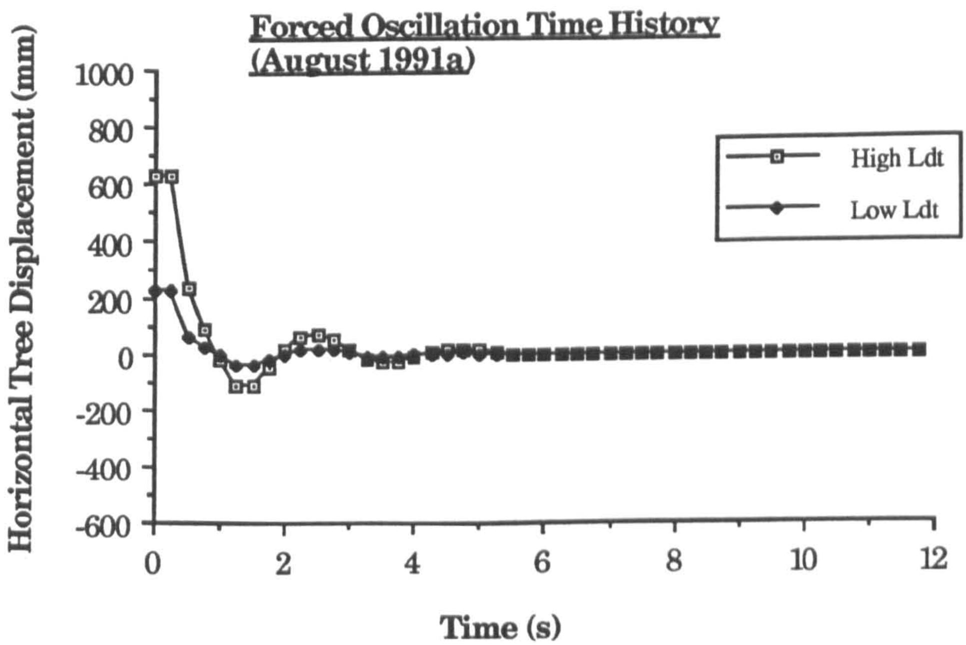


Figure 6.5 Trunk displacement time series - tree in leaf

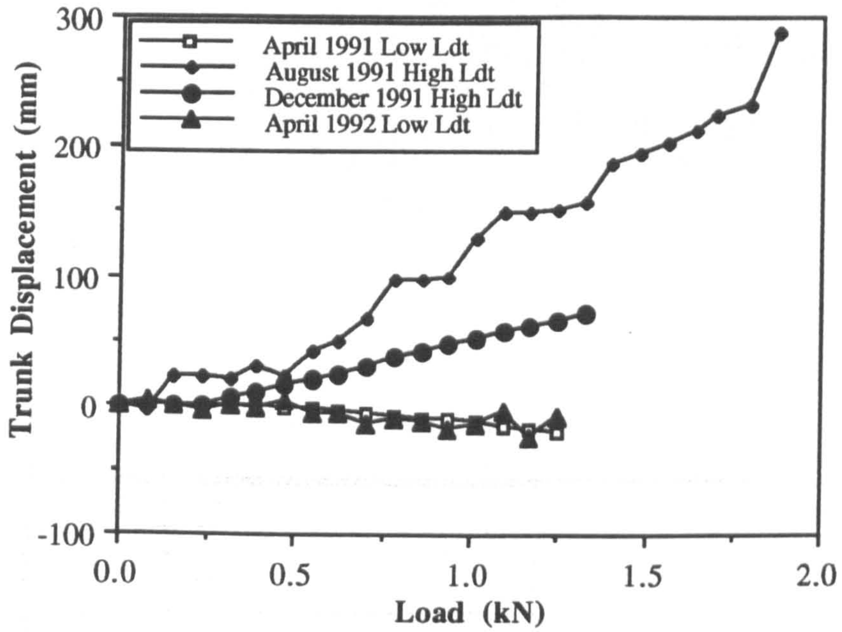


Figure 6.6 Load/ lateral displacement curve for the campus Platanus

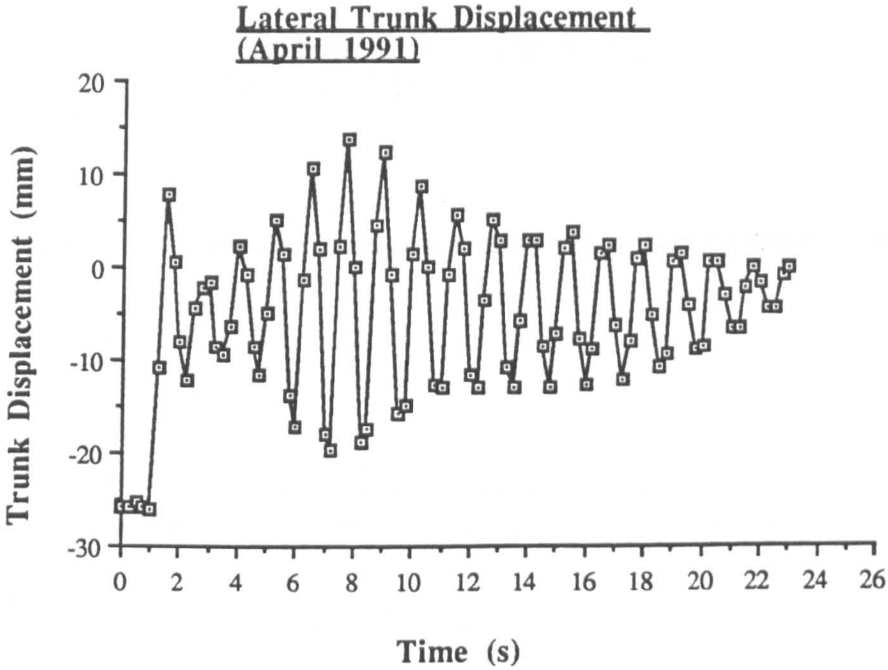


Figure 6.7 Lateral trunk displacement time series

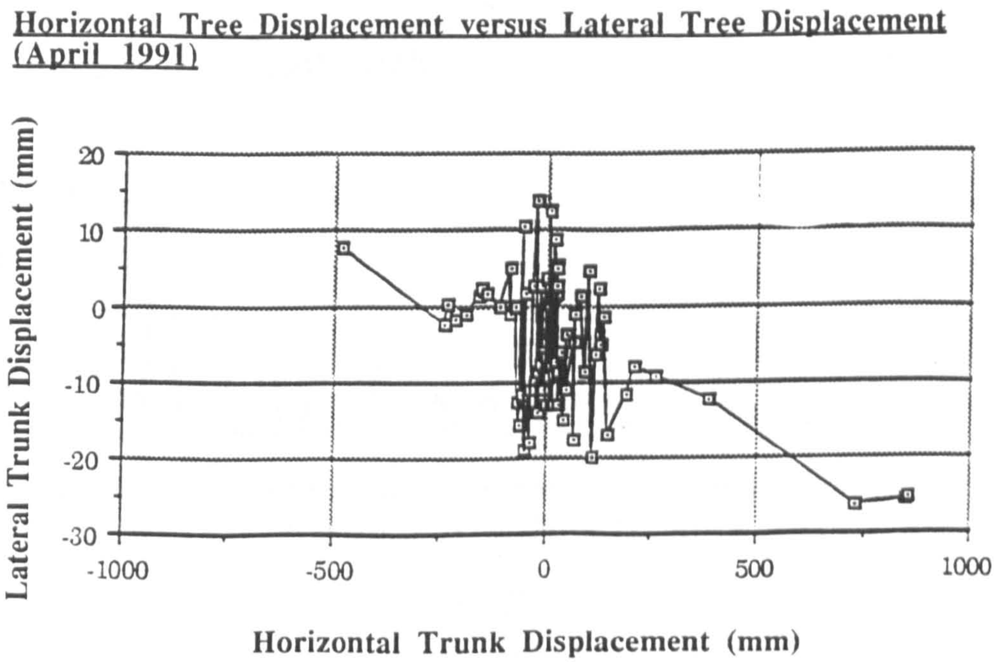


Figure 6.8 Trunk displacement in the direction of loading versus lateral trunk displacement

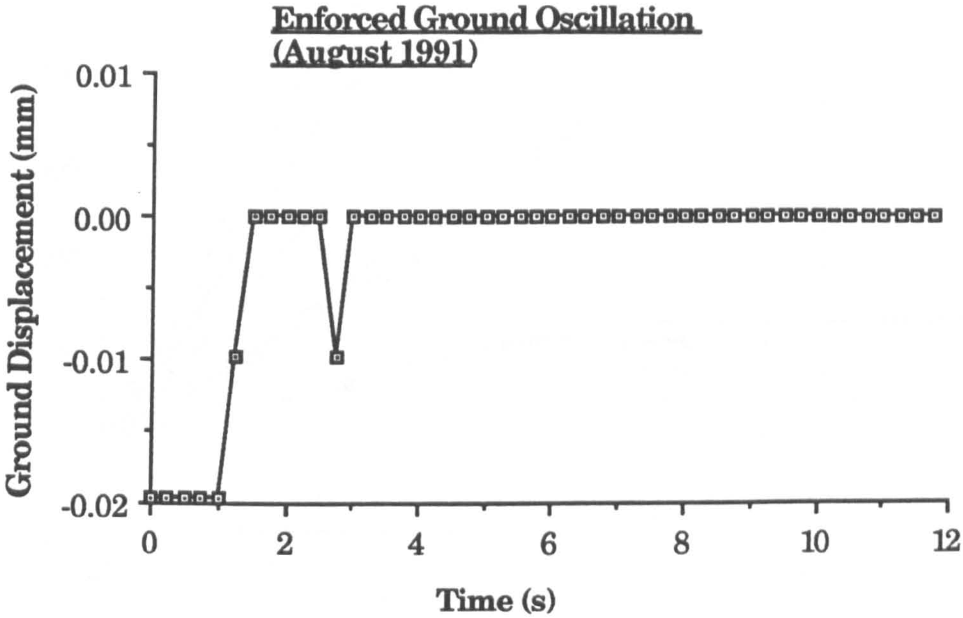


Figure 6.9 Ground movement - tree in leaf

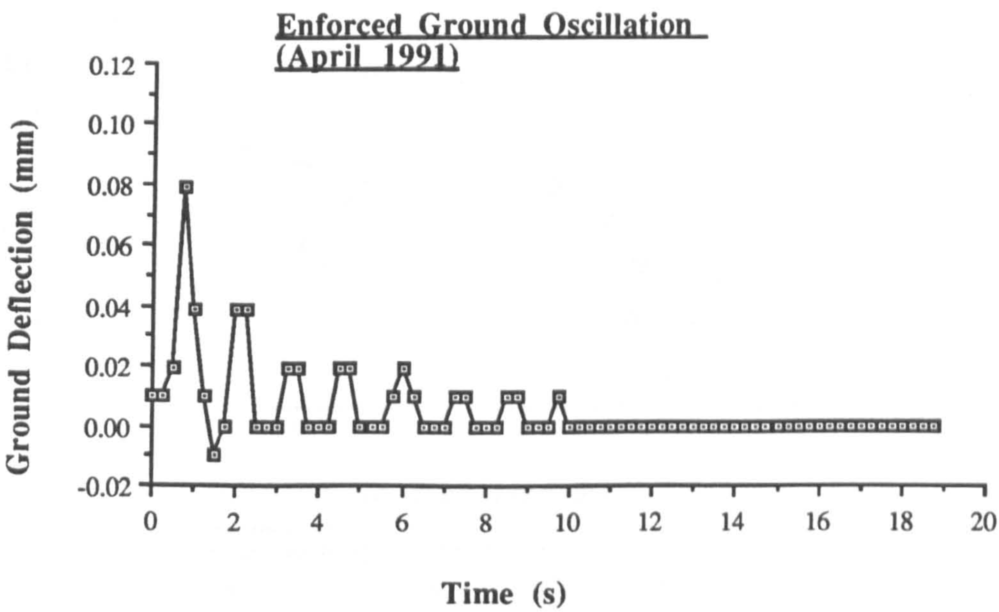


Figure 6.10 Ground movement - tree out of leaf

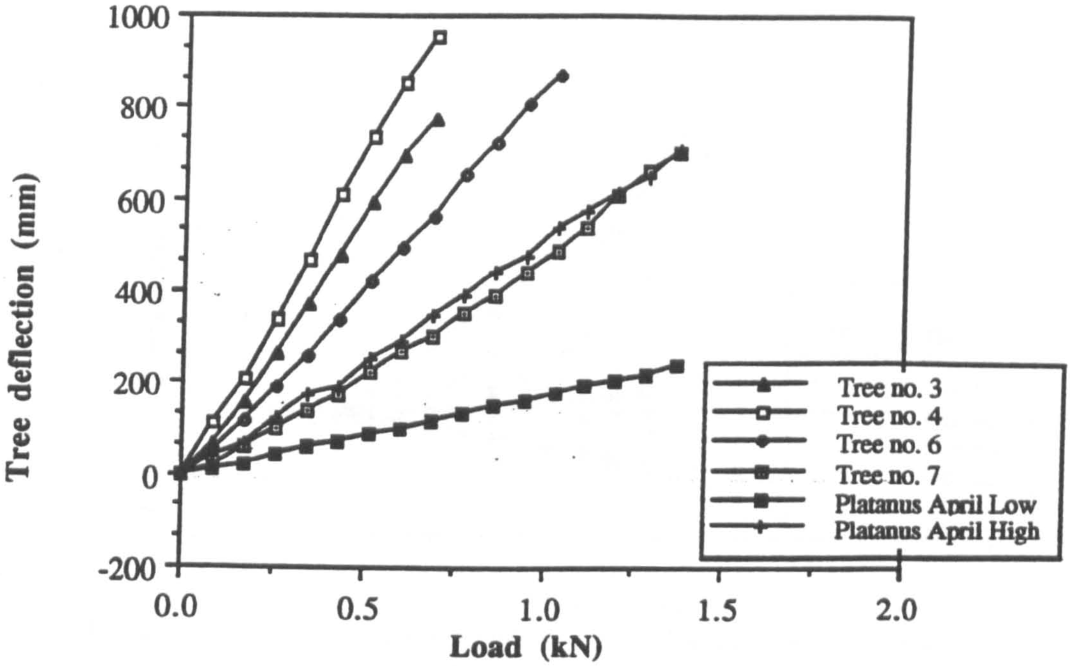


Figure 6.11 Load deflection curves for Blidworth trees

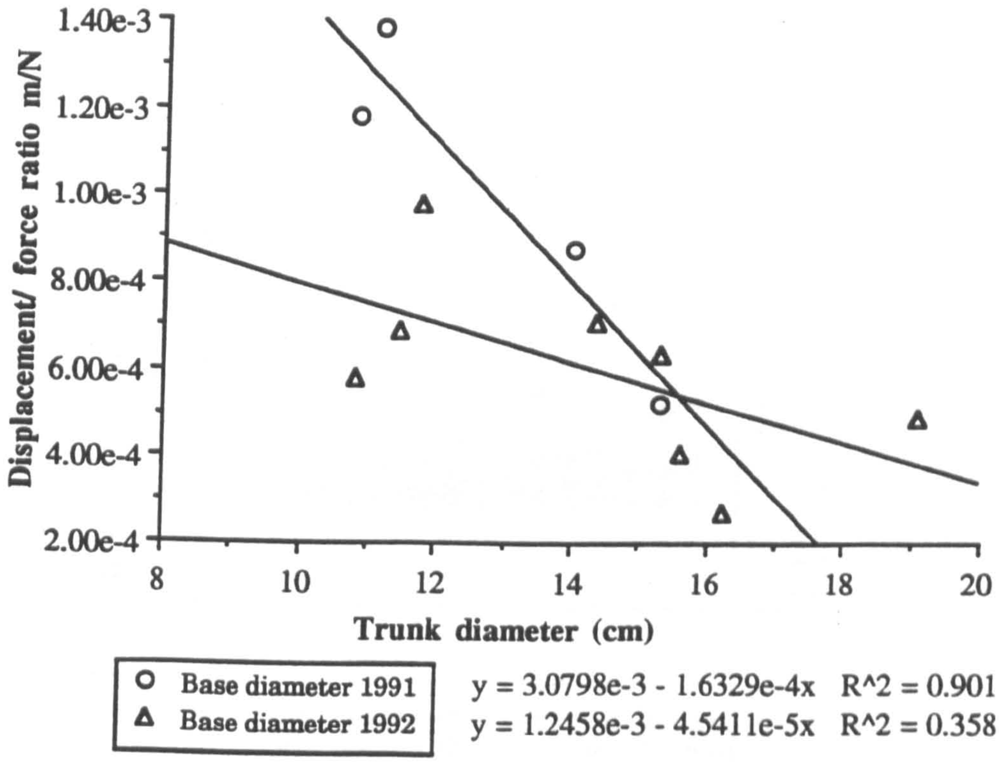


Figure 6.12 Displacement/ Force ratio versus trunk diameter Blidworth trees

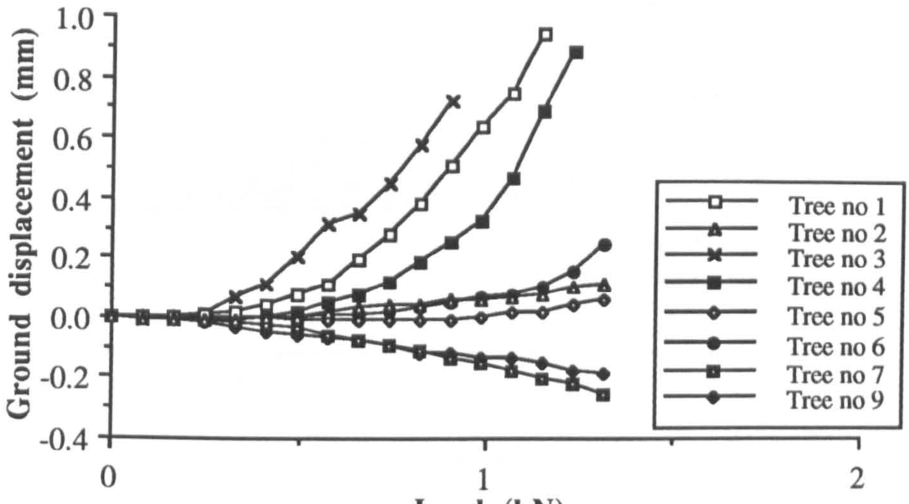


Figure 6.13 Load displacement curve for ground movement in the direction of loading (Blidworth 1992)

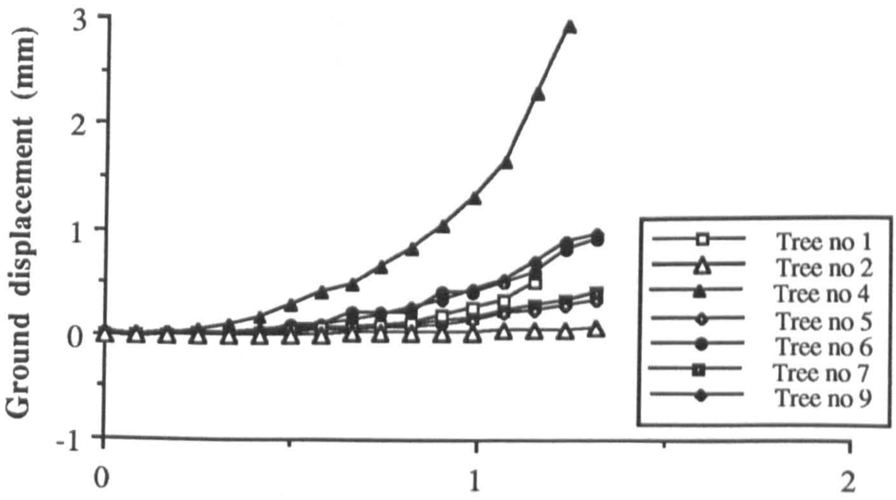


Figure 6.14 Load displacement curves for ground movement away from the direction of loading (Blidworth 1992)

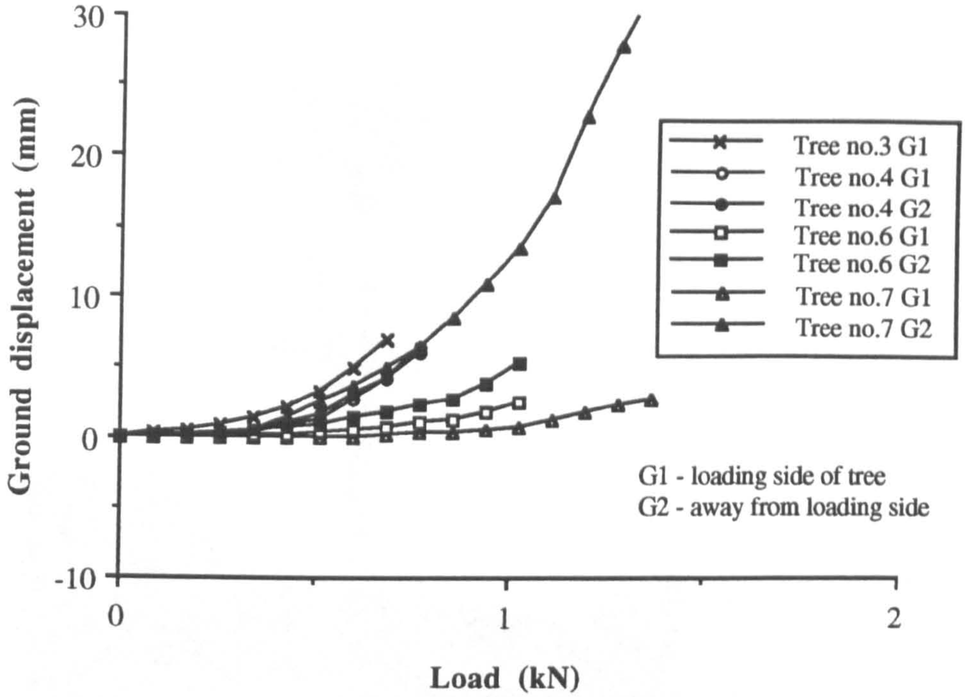
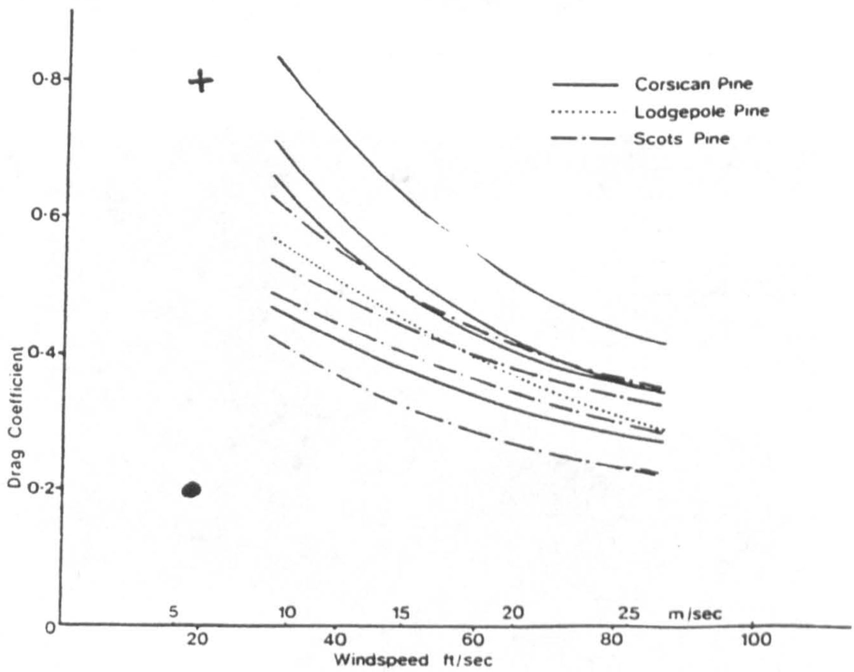


Figure 6.15 **Load displacement curves for ground movement - Blidworth 1991**



+ *Platanus* in leaf ● *Platanus* without leaf

Figure 6.16 **Drag coefficient of *Platanus* compared with other conifers (Mayhead 1973)**

Plate 6.1 - Street trees at Blidworth

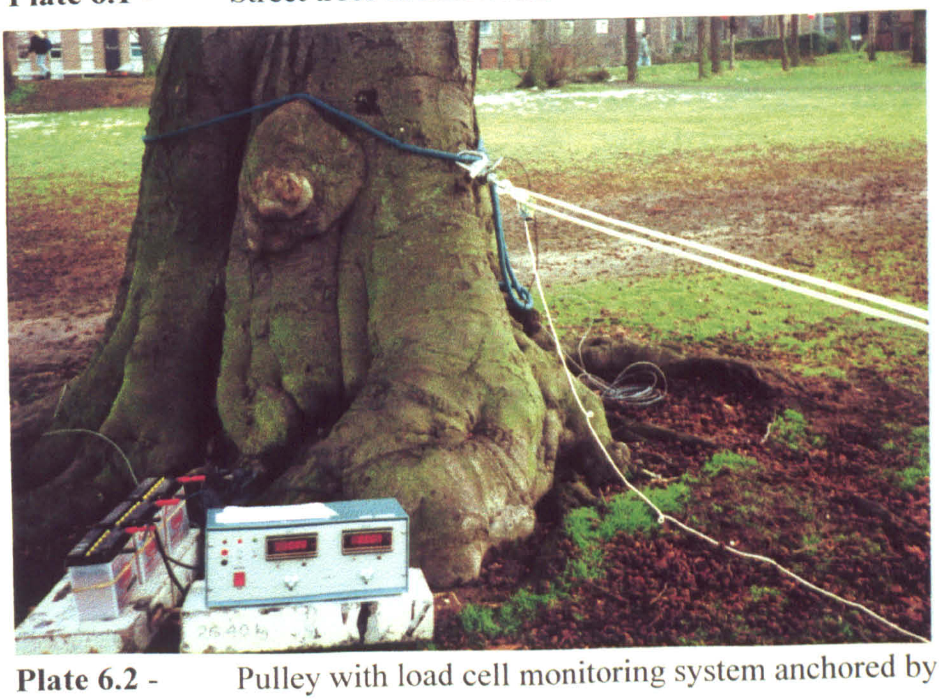


Plate 6.2 - Pulley with load cell monitoring system anchored by a tree

Plate 6.3 - Cutting the expendable strop

Plate 6.4 - Deflection of *Platanus acerifolia*

Chapter 7

Tree Uprooting

7.0 Introduction

The determination of whether or not a tree will be uprooted must ultimately involve the roots and soil. Small root movements were measured as part of the practical experimentation already reported in Chapters 5 and 6. However, those experiments were primarily to observe small trunk displacements and the tree was never subjected to forces which were likely to cause uprooting. The literature review gives values of maximum turning moments required to uproot forest grown conifers (Section 2.2.1). However, no details of the uprooting of broadleaf trees were available.

Two series of experiments were undertaken, both of which were exploratory in nature, both in terms of the experimental technique and the equipment used, as well as in the data obtained. Useful results were however gained from these experiments. The first series of uprooting trials took place on the University campus (Section 7.1), and the second at Blidworth (Section 7.2), using a number of the trees previously used in the forced oscillation experiments. Details of the experimental apparatus and procedure are given in each section followed by their results. Conclusions covering both series of uprooting trials are presented in Section 7.3.

7.1 Uprooting Campus Trees

7.1.1 Introduction

Due to the small number of trees available for uprooting, selection was minimal and did not include any mature isolated broadleaf trees. The specimens available were a number of *Acer pseudoplatanus.* These trees were growing in a relatively sheltered area in quite close proximity, though not as close or regular as a forest plantation (characteristics given in Table 7.1). The trees were self sown, (that is grown from the seed of the parent tree on uncultivated ground without human interference), and were estimated to be on average 15 years old, no planting dates being available. The uprooting experiments were carried out on the 27th and 28th February 1991.

7.1.2 Method

The crowns of trees were removed before experimental work began leaving a stump of approximately 2 metres. This was to ease experimentation and remove the danger and nuisance of small branches in machinery, thus also increasing the safety of the operators. The final analysis would also be simplified. It was assumed that the removal of crown weight would not significantly alter the uprooting forces, particularly as the form of the trees was that of a tapering trunk with small branches rather than a large crown.

The apparatus was assembled as shown in Figure 7.1, and Plates 7.1, 7.2, using a 2.5 tonne 'Tirfor' winch, anchored by a very large tree to apply the load. Loading was applied in stages of approximately 2.5 kN, monitored by a load cell connected to the same digital voltmeter as used in the forced oscillation experiments (Section 6.1.2). Loading, in most instances, was applied at a height of 0.5 m up the trunk from ground level, with exceptions being noted.

The apparatus for monitoring the root movement was the same as that described in Section 5.1.2 for the roots during windy periods. Movement was generally monitored at points 0.5 m in front of the tree, and 0.5 m and 1 m behind the tree, with respect to the direction of loading. When these precise locations were not possible a different arrangement was adopted, with the settings being noted. This root movement of the tree was recorded simultaneously with load application, until such a point where the apparatus was at risk of damage by crushing from the displaced tree trunk. It was then removed before final loading continued. Trunk displacement was determined by measuring the lateral movement of a marker on the winching wire.

Problems were encountered with the application of load to the stumps in that there was a degree of relaxation, by which the applied force appeared to lessen after pulling the wire by any particular distance. This problem had been encountered earlier in the static loading of the trees for the load/ deflection calibration (Section 6.1.2). The load had to be returned to its target load value before it could be increased to the next target load.

This relaxation and reloading process was later used as a method of uprooting the trees which did not uproot when the maximum possible load was first applied. In some instances this procedure was repeated several times before uprooting occurred. The period of relaxation was timed, before the load was returned to the target value.

A further problem encountered was the slipping of the strop on the trunk. This was minimised by cutting notches out of the trunk for the strop to rest in, and with the use of large clamps. When this still proved unsuccessful, the strop had to be relocated at a different position on the trunk. The distance of the strop from the ground was measured and thus the moment applied to the stump could be calculated.

A soil sample was taken from the ground following the removal of the one of the trees, and its moisture content by mass was measured to be 20.8 % (Appendix E). The soil was a sandy clay. Assuming a plasticity index of 10 - 20 % (TRRL 1979), the soil's undrained shear strength was estimated to be 50 kPa (TRRL 1979).

Once the stump was uprooted it was removed from the copse and photographed. Later the roots lengths and root diameters at breakage point were measured and recorded on photocopies of the photographs. The direction of load application to the stump was also noted.

7.1.3 Results of *Acer pseudoplatanus* uprooting

7.1.3.1 Uprooting forces

The maximum loads and turning moments required to uproot each stump, and the number of relaxation and reloading cycles required, in the cases where the 'Tirfor' limit was reached, are given in Table 7.2. The maximum turning moments were divided by trunk diameter at breast height, in each case, in an attempt to account for variation due to tree size (Table 7.2). This was also illustrated by plotting the maximum turning moments against the trunk diameter (Fig. 7.2). No distinct correlation was observed, however it should be noted that only three stumps (*Acer*s 3, 6, and 7), were uprooted without complications (described below). It was therefore decided to revert to the maximum turning moments and actual loads when discussing the results for the Campus *Acer*s.

The first tree pulled (*Acer* 1), reached the maximum loading which could be applied without uprooting and the roots were eventually axed.

Three trees (*Acers* 3, 6 and 7), with trunk diameters of 121 - 286 mm, were uprooted with loads of 17 kN, 12 kN and 7 kN. The turning moments were calculated to be less than 9 kNm.

Three other trees however (*Acers* 2, 4 and 5), withstood the maximum loading which could be applied by the 2.5 tonne 'Tirfor' winch, one even when the loading strop was raised to 0.75 m from the ground. Experimentation of raising the strop high to increase the turning moment was carried out, but it resulted in excessive bending in the trunk making it likely to snap, with no significant increase in root movement. Loading was thus restricted to 0.5 m from the ground.

Acer 2 required 8 relaxation/ reloading cycles before it was uprooted with a maximum turning moment of 14 kNm, whilst another, of a larger diameter (*Acer* 5) required only 4 cycles. The largest tree (*Acer* 4) uprooted in this experiment (440 mm trunk diameter at 0.75 m from the base), experienced strop slippage problems, requiring the strop to be reset and the experiment to be repeated three times, with also a number of relaxation cycles at each strop setting.

The relaxation cycles of *Acers* 2 and 4 are clearly illustrated in the ground movement monitored 0.5 m behind the stump (Figs. 7.3 and 7.4). Once the maximum load had be applied, time elapsed, after which the applied load appeared to have reduced. However, the ground displacement monitored was observed to be greater than for the same load when it had previously been applied. As the maximum load was reapplied after apparent relaxation, the stump was caused to deflect even further. This cycle was observed to occur a number of times before the stump was finally uprooted.

Although the force displayed on the monitor was shown to lessen after an elapsed time period, the loading system itself was not actually released. There may however, have been slight stretching within the components of the system - the wire cable or the strop. If the loading system were assumed to remain constant, this would suggest that any movement which occurred must have been due to the stump moving in the direction of the force. The direction of vertical ground movement would help in the determination of the relaxing element, whether it be the tree stump or the loading system. *Acer* 2, with 7 cycles, shows the relaxation to be due to stump movement, with the ground continuing to rise, all be it by very small amounts (Table 7.3). *Acer* 4 (Table 7.4), with 2 cycles on each of the first two loadings, show a very slight depression of the ground during the relaxation. This suggests relaxation of the loading system.

The repeated loading of *Acer* 4, following the strop slippages, produced three different trunk displacement curves (Fig. 7.5). The first two curves follow almost the same path, though the trunk displacement was slightly less on the second loading than on the first, for the same turning moment. This can perhaps be attributed to compaction of the soil during the first loading, and the stump not returning to its initial position before the reloading commenced. The third loading however, shows a considerable increase in trunk movement for all load values above 7 kNm. The first loading reached only values of 13 kNm, compared with 21 kNm on the second loading. It appears that this increased loading caused some irreparable damage to the tree rooting system, causing it to become less stable on subsequent loading. This suggests that there is perhaps a critical moment for the tree failing, between 13 - 21 kNm. This may have been the breakage of the soil/ root interface, or perhaps even the snapping of roots.

This reloading must not be confused with the relaxation and reloading patterns observed when the maximum turning moments were applied. In this instance all loads were removed from the stump, as the strop was relocated. Reloading was then started again from zero. In the relaxation curves described earlier, the length of the loading cable was maintained, that is, the system applying the load was not relaxed.

Trunk displacement was observed generally from the first loading, which was before ground movement was recorded. Initially, for the small load applied, the trunk displacement was approximately linear. As the load increased, the increased displacement was no longer linear - disproportionately greater increases in displacement occurred when progressively greater forces were applied (Shown by *Acer* 3 in Fig. 7.6). The values of the moment/ trunk displacement ratios for the application of small loads, within the elastic limit (Table 7.5), corresponded well with the maximum turning moments required to uproot each tree. The following caution should however be noted:- The trunk displacement was measured at the height of the strop, which varied, notably, for *Acer* 4. For the initial loading (run 1), the trunk displacement was measured at 0.5 m, and at 0.75 m on the second and third loadings. This may help to explain why more load was apparently required on the second loading to produce the same size displacement. On the third loading however, supporting the soil compaction hypothesis, still more loading was required to produce the same displacement. In this instance, the elastic part of the curve ranges over only four readings unlike runs 1 and 2 where twice as many readings were taken in the elastic range.

Ground movement monitored during the uprooting process was discernible following the application of a turning moment of approximately 5 kNm to the stump (Fig. 7.7a). The ground immediately behind the trunk, (that is opposite to the side of loading, at a distance of 0.5 m) was observed to rise in all cases. The movement was as much as 30 mm in some cases after the application of 14 - 26 kNm.

The ground at 1 m behind the tree lifted in the case of *Acer* 3, but no visible movement was detected in the case of *Acer* 4.

The ground in front of the tree, 0.5 m or 0.75 m from the trunk, was observed to be slightly depressed in two instances (*Acer*s 4 and 5), though only to 1-2 mm (Fig. 7.7b). On other trees the ground was seen to rise, though to a slightly smaller amount than the ground behind the stump. Visual observation noted that the rise in front of the tree was due to the compression of soil as the tree was pulled horizontally along the ground. The force applied caused this horizontal movement as well as the rotation due to the turning moment.

The trunk displacement of *Acer* 4 was considered simultaneously with ground displacement. This showed that on the first loading, initial trunk displacement was greater per unit of ground displacement than on the second loading (Fig. 7.8a). After this initial displacement, the trunk displacement appeared to increase with increasing ground displacement, - at the same rate for both loadings. This again supports the soil compaction hypothesis. The increasing trunk and ground displacements suggest that the trunk and soil root-plate are moving together as a unit. However, on the third loading, there was a dramatic increase in trunk displacement compared with the increasing ground displacement (Fig. 7.8b). This suggests that the trunk and soil are no longer reacting to loading as one unit, perhaps the roots have snapped and are being pulled through the soil, and not moving the soil with them. This theory was supported when the stumps were finally uprooted. They had very little soil attached as a soil/ root-plate, and very long protruding roots.

This finding however appears not to model the more mature trees which were observed in the F.C., Kew and author's own surveys, the majority of which had a large soil root-plates (averaging 3.2 m) from which only a few long roots protruded.

7.1.3.2 Root structure

The uprooted stumps were generally of a form with roots radiating laterally from the base of the trunk at a shallow depth in the soil (Plate 7.3). These roots were generally evenly distributed around the trunk, with the exception of *Acer* 5 which had no roots in the direction opposite to the applied load (Plate 7.4). This tree however, still required the maximum possible load, and 4 relaxation/ reloading cycles. This tree appeared very stable despite the theory promoted by Coutts (1983) which suggested that the roots effectively on the side from which the wind was blowing would be responsible for a major part of the resistance.

Most of the stumps had little soil attached to the roots, but on two, *Acers* 4 and 7, there was a small soil/ root-plate (Plate 7.5). All but the smallest roots were broken at some point in there length, with the diameters at the point of root breakage varying from 1- 40 mm. Most roots had undergone slippage through the soil, before or after breaking. A summary of the root dimensions, length and diameter at breakage point, is given in Table 7.6. The maximum root length recorded for any of the trees was 2.7 m for *Acer* 5. The average root length was 0.75 m, hence an average root-plate diameter would be 1.5 m. These values are comparable with the F.C. survey, which recorded a maximum root-plate diameter of 9 m, and also with the Kew survey which found root-plate radii to be generally less than 2 m (Section 3.3.4.1).

The majority of roots were laterals, growing within the surface layers of the soil, but a small number were growing vertically downwards into the soil. These vertically growing roots were found to be of a maximum length of 1.3 m in the uprooted soil root-plate, with an average of 0.71 m. Roots extending below the soil root-plate, if any, were of very small diameter. These values again are similar to those in both the F.C. and Kew surveys (Section 3.3.4.1). *Acer* 7 however varied from this form of root structure, in having a two tier root system, with two radial whorls of laterals one below the other (Plate 7.6).

There was no direct correlation between the turning moment required to uproot the tree and the number of roots each tree had, nor the average root length of each tree. Also whether the tree had one or ten vertically descending roots did not appear to be directly related to the turning moment required to uproot the tree.

However, further possible reasons for the lack of correlation were found when the roots were closely examined. The roots of *Acer* 1 were found to be intertwined with those of another tree, which was thought to add to its stability. *Acer* 2 was found to have roots which had actually fused to roots of a neighbouring tree. The extra stability gained by this feature, to some extent explains the requirement of 8 relaxation/ reloading cycles before uprooting.

7.2 Uprooting of the Blidworth trees

7.2.1 Introduction

A total of ten trees were uprooted at Blidworth, although one of these was not monitored other than for the maximum applied force. Most of the trees were those already monitored in the forced oscillation experiment (Chapter 6). They included *Sorbus aria, Acer saccharinum*, and *Platanus acerifolia*. Characteristics of the trees are given in Table 7.7, with details of the direction of loading, and the height at which the load was applied to the tree. The uprooting of these trees occurred on the 18th and 19th May 1992.

7.2.2 Method

The method was similar to that used on the campus trees (Section 7.1.2), with some minor modifications. As there was no means of anchoring a winch, the load was applied by a winch mounted on the front of a Landrover. Loading was applied slowly, controlled by the Landrover's accelerator, which although not as sensitive as the Tirfor winch, provided a good range of values monitored on the digital voltmeter and recorded on the datalogger.

Slippage of the strop up the trunk had proved to be a major problem during the uprooting experiments on the Campus. For the Blidworth experiments, a clamp was specifically designed and made to further reduce the slippage problem (Plate 7.7).

The movement of the stump was monitored by a linear transducer mounted on the tree at a height of 39 cm, on the side away from the direction of loading. A second method was also implemented. This involved the horizontal movement of a metre rule attached to the trunk, but with free radial movement (Plates 7.8 and 7.9). Horizontal displacement was monitored by observing the metre rule as it passed the cross hairs of a level mounted on a tripod, approximately 10 metres away. This method was tested during the forced oscillation experiments when correlations of displacement were made with that recorded by the linear transducer attached to the trunk.

The stump movement was also monitored by measuring the distance moved by the loading wire on subsequent load values, as with the campus trees.

Ground movement was monitored in most instances by two ground-mounted linear potentiometers as in earlier experiments. These were removed during the uprooting process when they appeared to be at risk of damage by the moving stump.

In this uprooting experiment, like the Campus *Acers*, a small number of trees withstood the maximum forces which could be applied to them with the equipment available. The technique of relaxation and reloading was not used here, instead a pivot was used to aid the uprooting. The pivot was a tree trunk placed on the ground close to the trunk of the stubborn tree on the loading side (Fig. 7.9). The pivot provided a specific point about which the stump could rotate and also acted partially to prevent the slippage of the tree stump through the soil.

Following the uprooting, photographs were taken, and visual observations noted. On this occasion, unlike the campus *Acers*, the length and diameters of the roots were not measured, partly due to a tight schedule, and also due to the form of the root-plates themselves when they were uprooted.

7.2.3 Results of the uprooting of Blidworth trees

7.2.3.1 Uprooting forces

The maximum turning moments required to uproot the Blidworth trees varied from 2.24 kNm to 4.72 kNm (Table 7.8). These turning moments were related to tree size using the trunk diameter, as in Section 7.1.3.1 and Table 7.2. Trunk diameters varied from 8.3 cm to 12.7 cm. Six of the ten specimen trees were uprooted without complication. Of these six examples, five appeared to indicate a positive relationship between trunk diameter and maximum turning moments (Fig. 7.10). However as the turning moments of only half the trees could be related to tree size, it was again decided to present the following results in terms of turning moments applied.

Of the six trees which uprooted without complication (nos. 1, 2, 3, 4, 5, 9), 4 were *Sorbus aria*, 1 was *Platanus*, and 1 was *Acer saccharinum*.

Two trees, an *Acer saccharinum* and a *Sorbus aria* (nos. 7 and 8) were not uprooted by the maximum load which could be applied by the Landrover. Subsequently, with a pivot placed in front of the tree, turning moments of 3.80 kNm and 3.89 kNm respectively caused uprooting. These trees had trunk diameters of 11.8 cm and 9.5 cm respectively, which were not the largest of either species.

Moment/ trunk displacement ratios were again calculated for trees over their elastic range of trunk displacement (Table 7.9). The first five trees tested showed a good correlation with the ultimate uprooting turning moments. Tree 6 initially had a high moment/ displacement value and eventually required three attempts at uprooting, one of which was in the opposite direction. Higher uprooting moments would have been expected for trees 7 and 8. However, these two trees did not uproot without complication, and required a pivot to aid uprooting, thus effectively lowering the recorded uprooting turning moment. The only exception to the trend, appeared to be tree 9, which again had a high moment/ displacement value, but uprooted relatively easily with a turning moment of only 2.98 kNm.

Two of the trees (nos. 6 and 10), both *Platanus,* experienced trunk breakage as opposed to uprooting. The *Platanus* (no. 6), had no visible signs of weakness before the loading began. This tree was loaded first from one side at 1.5 m, then when it appeared destined to snap the load was removed and applied at 0.5 m. Maximum load was applied but this was insufficient to uproot the tree. The load was again removed and reapplied at 1 m up the trunk, but this time from the opposite direction. The applied load still did not cause the stump to uproot, but caused it to split. The other *Platanus* stump (no. 10), had a visible weakness at the base of the trunk before loading commenced, as well as being without a crown. The third *Platanus* (tree no. 2) however, (incidentally with the largest trunk diameters of the *Platanus*) uprooted with a turning moment of 4.72 kNm, without any complications. The F.C. survey however, found the uprooting of *Platanus* more common than crown breakage (Fig. 3.8).

7.2.3.2 Root structure

The roots of these trees appeared to be of a very different form to that of the Campus *Acers*. The roots were not radiating laterally, nor even descending vertically. They were generally deeper than those found on the Campus, but were spirally twisted below the base of the tree. Almost all the roots were contained within the pit, approximately 1 m^2, which had been excavated to plant the tree in. Measurements were not taken of the root-plates but photographs with a scale present, illustrate the observations (Plate 7.10, 7.11). The roots were generally lifted intact, and so the lengthy procedure of root diameter and length measurements was not undertaken. It was thought that this very compact root structure contributed greatly to the relative instability of these trees compared with the Campus *Acer*s. It may also help to explain why the maximum turning moment appeared constant for the varying trunk diameter. The turning moment is probably related principally to the pit size, which was fairly constant.

It was noted that the *Acer saccharinum* had very fibrous roots compared with the other species, but they too followed the spiralling pattern within the pit.

7.3 Discussion

The turning moments required to uproot the Blidworth trees were much lower than those required by the Campus *Acers* (by a factor of 4). It was noted however, that the Blidworth trees had smaller trunk diameters, on average approximately half that of the Campus *Acer*s. Although reservations have been expressed over relating this uprooting moment to trunk diameter, it was found that if these values (Tables 7.2, and 7.8), are averaged, then values of the Campus *Acer*s is now only greater by a factor of 2. Trunk diameter (or tree size), even if it were related directly to the uprooting moments, would not therefore be the sole factor responsible for the much lower turning moments of the Blidworth trees. Other reasons became apparent when the inferior rooting systems of the Blidworth trees were observed.

Turning moment/ trunk displacement ratios for trees over their elastic range of trunk displacement were calculated for the *Acers* (Table 7.5) and Blidworth trees (Table 7.9). Both sets of results revealed a trend, in that the slopes of the initial moment/ displacement curve correlated well, with the final uprooting moments (exceptions noted). The Blidworth values however were not directly comparable with those of the Campus *Acers*, due to the trunk displacement being measured at a height of 0.39 m as opposed to 0.5 m of the *Acers*. However, it was apparent that the maximum values were less, which corresponds also with the lower forces involved in the ultimate uprooting.

The turning moment of the stump appeared not to be the only force involved in the uprooting. This became obvious when the moments of the forced oscillation experiments were considered. Although the load applied to the top of the tree was less than that applied at 1 m height when uprooting, the turning moments were not vastly different (Table 7.10). In fact the turning moment in the forced oscillation experiment was most often found to be greater than that in the uprooting experiment. The trees in the forced oscillation experiment were however in no danger of uprooting at all, with only a deflection of approximately 15^{0}. This observation was supported by the varying range of movement of the trunk at 2m, (measured by viewing the metre rule through the level). In the forced oscillation experiments the displacement was of the order of 10 cm compared with that of greater than 100 cm during the uprooting experiments for similar values of turning moment. It would seem therefore that the turning moment was not solely responsible for the uprooting observed here.

It should also be noted that the load applied to the tree during the oscillation experiments was applied at an angle (Fig. 6.1). The horizontal force was thus calculated using the cosine of the pulling angle. The vertical component of this loading would be acting downwards along the axis of the tree. The influence of this vertical force on the behaviour of the tree was unknown.

The loading during the uprooting experiments would also have caused a rather large shear force at the base of the tree (Table 7.10), especially when compared with that induced by the forced oscillation loading. This was confirmed by the ground movement recorded at the base of the tree. If the tree was being uprooted solely by turning moments, the ground would be expected to sink on the loading side, but rise on the far side (Coutts 1983), and as observed in the storm survey results (Section 4.3.3). The soil was however observed to rise on both sides of the tree. This suggests that the loading during uprooting was effective also in pulling the stump horizontally through the ground, causing the soil to be compressed and thus rise upwards. The difference in the ground movement from those trees observed by Coutts (1983), may have been due to several reasons. The trees in Coutt's experiment were conifers with shallow, spreading plate-like root systems, with little resistance to rocking, compared to the deeper pit-bound roots at Blidworth. The size of the trees involved may also be a significant factor. The conifers were up to 21 m high and 35 years old, and would have required a greater force to move the tree base horizontally than the much smaller trees at Blidworth.

Coutts (1986), summarised the forces involved in the uprooting process and their importance at each stage of uprooting. This was done on the basis that the uprooting process was brought about solely by a turning moment and the weight of the tree once the centre of gravity was displaced from the vertical. Fraser (1962) also only considered the uprooting forces to be turning moments. The uprooting experiments at Blidworth however, indicate a need for caution when projecting values gained from uprooting experiments to wind speeds required to cause the uprooting. This is because of the differences in loading, at the base of the tree as in the uprooting experiments, or at the crown as in wind loading. The turning moments experienced by the tree under the different loadings may be similar, but the horizontal shear forces will be far greater when the loading is applied at the base of the tree.

7.4 Conclusion

The campus *Acers*, with trunk diameters of 121 mm to 286 mm, uprooted with turning moments of 10 kNm or less. The Blidworth trees with smaller trunk diameters averaging 90.4 mm, and average height of 7.3 m had turning moments of 2.24 kNm to 4.72 kNm. These compare well with turning moment of 3 - 14 kNm measured by Blackburn, Petty and Miller (1988), for 10 m high *Picea sitchensis.*

When the loads applied to the tree during the forced oscillation experiments are considered, it was seen that the loads were much smaller than those required to uproot the trees, as would be expected. However, if these loads were considered in terms of moment forces acting at the base of the tree, it was found that these moments would be greater than those applied during the uprooting experiments. This suggested that the uprooting forces as measured in the uprooting experiments, were not reliant solely on the turning moment, but are also influenced by the horizontal magnitude of the component of the pulling force.

Tree winching with the load applied close to the base of the trunk, does not adequately simulate wind effects, as much greater horizontal shear forces at the ground level are produced. Winching, with the load applied at a higher level was not practical either, as the trunk was observed to bend excessively, making it much more likely to break than for the stump to be actually uprooted.

Other forces too, such as the weight of the tree acting downward and the ground's vertical reaction will add complications, as will variations in the soil moisture content.

The ratio of turning moment/ trunk displacement at the initial loading values, before the elastic limit is exceeded, indicates the turning moment at uprooting. This could be a very useful observation in assessing the strength of the tree's root system, although it is as yet only a relative measure, and not thought to correlate with the trees stability in windy conditions.

Tables : Chapter 7

Tree identification	Trunk diameter at strop height (mm) (strop height (m))	Trunk diameter at 1.3 m (mm)	Trunk diameter at base (mm)
Acer 1		127	191
Acer 2	(0.5) 203	172	210
Acer 3	(0.5) 337	286	461
Acer 4	(0.75) 440		
Acer 5	(0.5) 320	223	334
Acer 6	(0.5) 225	159	286
Acer 7	(0.5) 160	121*	229

Table 7.1 Characteristics of uprooted *Acers* on campus
*** denotes trunk diameter of largest fork**

Tree identification	Maximum turning moment required for uprooting (kNm)	Maximum turning moment divided by trunk diameter at 1.3 m (kN)	Number of relaxation and reloading cycles
Acer 1	> 40.00	315	Roots axed
Acer 2	13.80	80.2	7 cycles
Acer 3	8.73	30.5	0 cycles
Acer 4	14.70, 20.77, 26.40	42.0, 59.3, 75.0	2,2,3 cycles *
Acer 5	11.97	53.7	4 cycles
Acer 6	6.08	38.2	0 cycles
Acer 7	3.30	27.3	0 cycles

Table 7.2 Maximum turning moments required for uprooting
*** strop was repositioned twice due to slipping, tree loaded first at 0.5 m, 0.75 m and 0.75 m from the roots respectively**

Ground movement during elapsed time (Relaxation) (mm)	Ground movement on reapplication of maximum load (mm)
0.12	
	1.21
0.40	
	2.53
0.21	
	1.33
0.17	
	1.88
0.20	
	6.04
0.02	

Table 7.3 Ground movement recorded by the linear potentiometer (no. 2), 0.5 m behind *Acer* 2 during the relaxation and reloading cycles in the uprooting process

Ground movement during elapsed time (Relaxation) (mm) Run 1	Ground movement on reapplication of maximum load (mm) Run 1	Ground movement during elapsed time (Relaxation) (mm) Run 2	Ground movement on reapplication of maximum load (mm) Run 2
-0.11		-0.09	
	0.98		1.37
-0.04		-0.06	
	0.64		

Table 7.4 Ground movement recorded by the linear potentiometer (no. 2), 0.5 m behind *Acer* 4 during the relaxation and reloading cycles in the uprooting process (2 runs).

Tree	Slope of turning moment/ trunk displacement curve in elastic range (kNm/m)	Height at which trunk displacement was measured (m)
Acer 3	28.6	0.5
Acer 4 run 1	78.6	0.5
run 2	100	0.75
run 3	125	0.75
Acer 5	125	0.5
Acer 6	3.6	0.5
Acer 7	3.3	0.5

Table 7.5 Turning moment/ trunk displacement ratio in the elastic range for *Acers*

				Lateral roots						Vertical roots	
Acer No.	no. of lateral roots	no. of vertical roots	total	Min. length (cm)	Max. length (cm)	Mean length (cm)	Min. diameter (mm)	Max. diameter (mm)	Mean diameter (mm)	Mean length (cm)	Mean diameter (mm)
1	31	1	32	20	104	77.0	1	17	3.2	20.0	40
2	31	10	41	30	251	135.3	2	16	7.3	83.2	5.0
3	28	10	38	13	130	49.7	0	40	8.8	68.0	5.0
4	-	-	-	-	-	-	-	-	-	-	-
5	26	1+	27	26	270	47.7	2	10	4.5	62.0	13
6	20	2	22	16	86	33.3	0.5	10	3.0	57.0	10
7	23	6 *	29	32	186	91.7	2	80	10.6	43.7	19.7

Table 7.6 Dimensions of the roots of the *Acers* : length and diameter at breakage point

Tree number	Species	Height (m)	Circumference at 1.3 m (cm)	Subject of oscillation experiments
1	*Sorbus aria*	5.22	26	once
2	*Platanus acerifolia*	8.20	34	once
3	*Sorbus aria*	9.82	27	twice
4	*Sorbus aria*	5.07	27	twice
5	*Sorbus aria*	8.40	31	once
6	*Platanus acerifolia*	7.13	33	twice
7	*Acer saccharinum*	7.37	37	twice
8	*Sorbus aria*	-	30	no
9	*Acer saccharinum*	7.45	40	once
10	*Platanus acerifolia*	stump only	26	no

Table 7.7 Characteristics of experimental trees at Blidworth

Tree number	Species	Maximum turning moment (kNm)	Maximum turning moment divided by trunk diameter (kN)	Comments
1	*Sorbus aria*	2.24	27.08	
2	*Platanus acerifolia*	4.72	43.61	
3	*Sorbus aria*	3.83	44.58	
4	*Sorbus aria*	3.59	41.78	
5	*Sorbus aria*	4.38	44.39	
6	*Platanus acerifolia*	3.72	35.41	3 attempts Trunk split
7	*Acer saccharinum*	3.80	32.26	Pivot used
8	*Sorbus aria*	3.89	40.75	Pivot used
9	*Acer saccharinum*	2.98	23.40	
10	*Platanus acerifolia*	3.48	42.03	Snapped at base

Table 7.8 Maximum turning moments required to uproot Blidworth trees

Tree number	Species	Slope of turning moment/ trunk displacement curve in elastic limit (kNm/m)
1	*Sorbus aria*	6
2	*Platanus acerifolia*	37
3	*Sorbus aria*	9
4	*Sorbus aria*	9
5	*Sorbus aria*	15
6 - run 1 - run 2 - run 3	*Platanus acerifolia*	33 16 7
7	*Acer saccharinum*	36
8	*Sorbus aria*	14
9	*Acer saccharinum*	34

Table 7.9 Turning moment/ trunk displacement ratio in the elastic range for Blidworth trees

Tree no. and species	Forced oscillation load (kN)	Forced oscillation moment (kNm)	Height of load and measured displacement (m)	Trunk displacement (mm)	Uprooting load (kN)	Uprooting moment (kNm)
1 *Sorbus aria*	1.18	3.04	2.58	691	2.24	2.24
2 *Platanus acerifolia*	1.35	4.93	3.65	524	4.72	4.72
3 *Sorbus aria*	0.75	2.68	3.57	608	3.83	3.83
4 *Sorbus aria*	1.27	4.25	3.35	791	3.59	3.59
5 *Sorbus aria*	1.35	4.73	3.50	810	4.38	4.38
6 *Platanus acerifolia*	1.32	5.16	3.91	1108	3.72	3.72
7 *Acer saccharinum*	1.34	4.80	3.58	353	3.80	3.80
9 *Acer saccharinum*	1.34	5.74	4.28	607	2.98	2.98

Table 7.10 Loads and turning moments applied to the Blidworth trees during forced oscillation and uprooting experiments

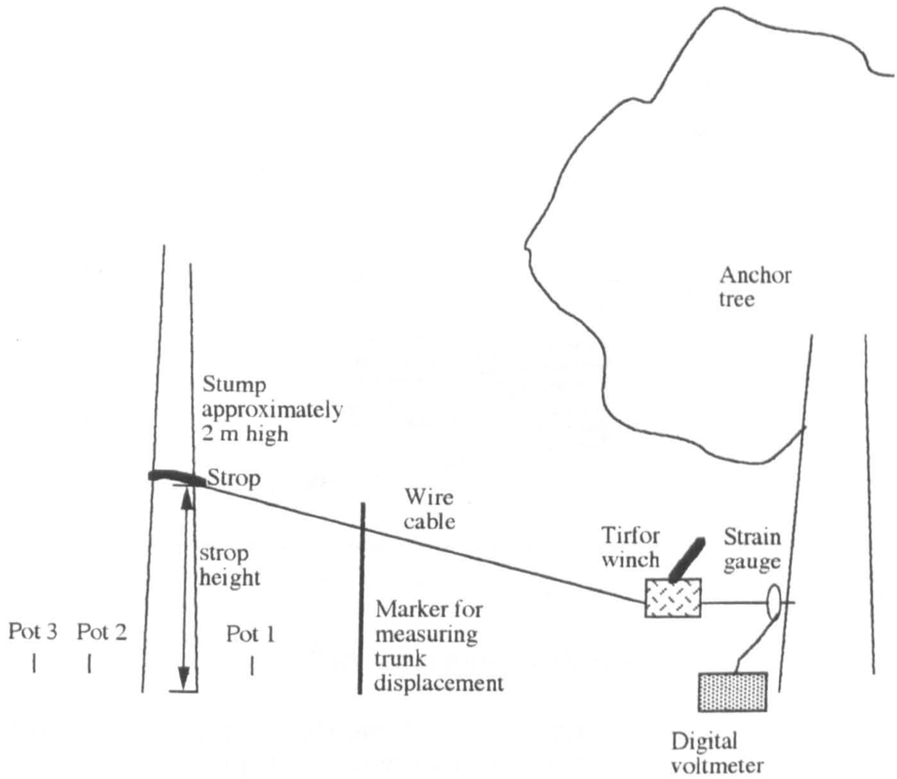


Figure 7.1 Apparatus for uprooting for exact location of strop and pots see Appendix D

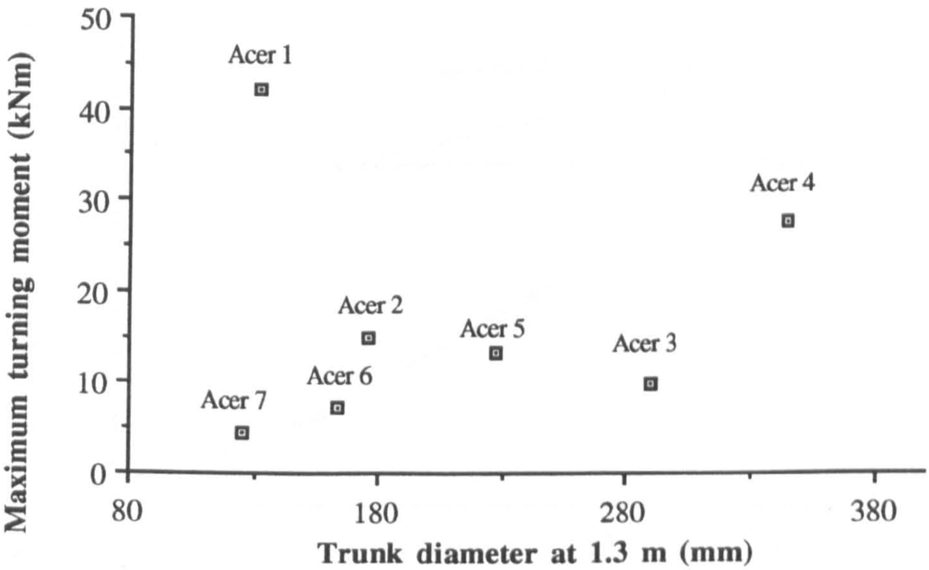


Figure 7.2 Maximum turning moment versus trunk diameter - Acers

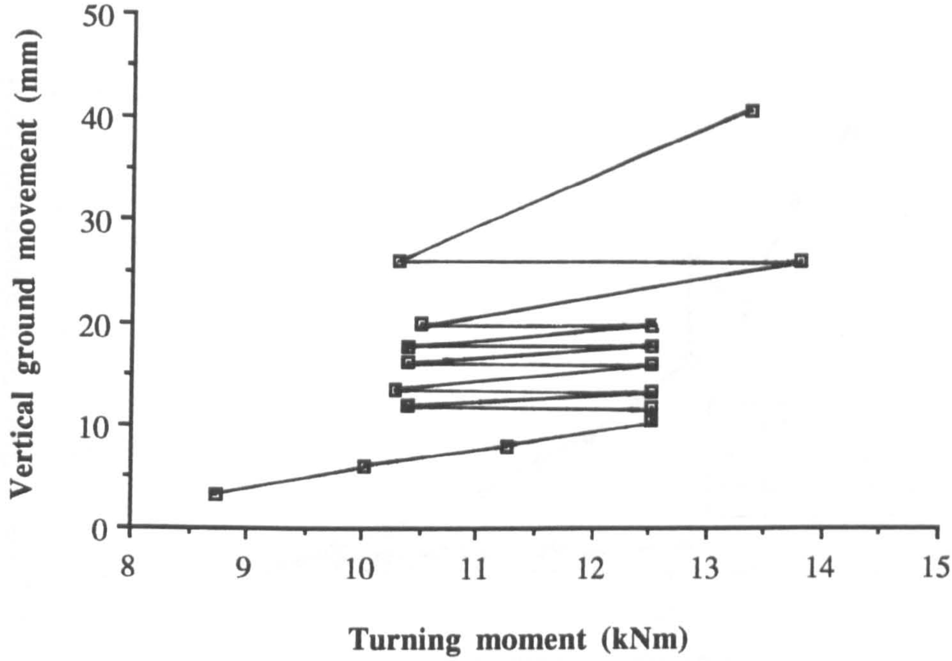


Figure 7.3 Ground movement 0.5 m behind Acer 2 during relaxation and reloading cycles

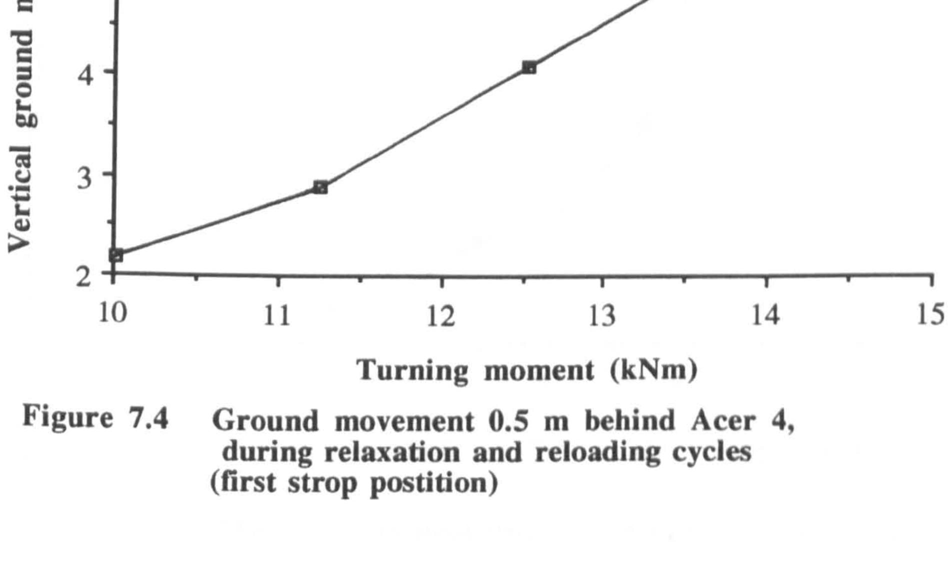


Figure 7.4 Ground movement 0.5 m behind Acer 4, during relaxation and reloading cycles (first strop postition)

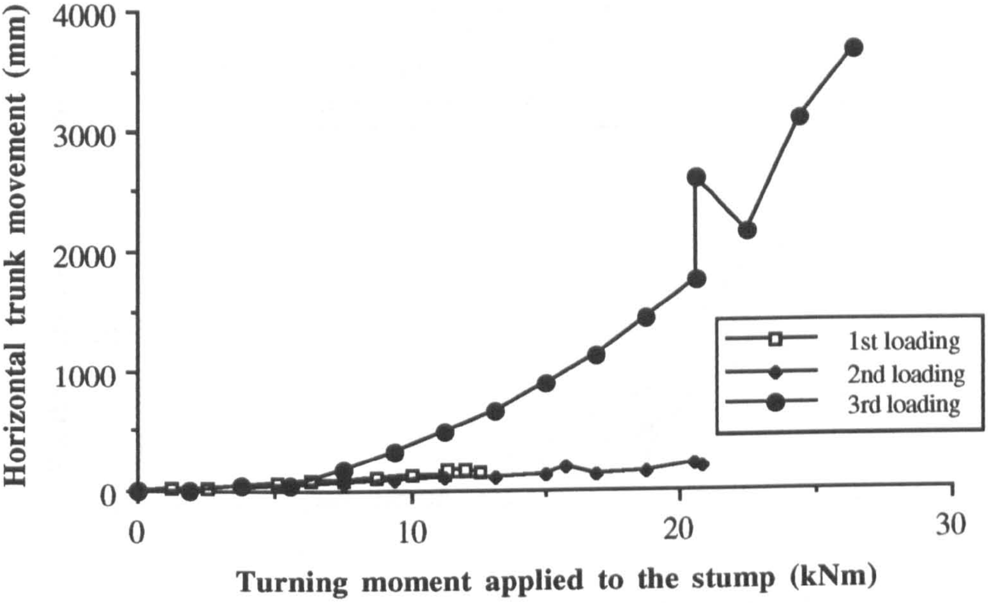


Figure 7.5 Trunk displacement during the uprooting of Acer 4

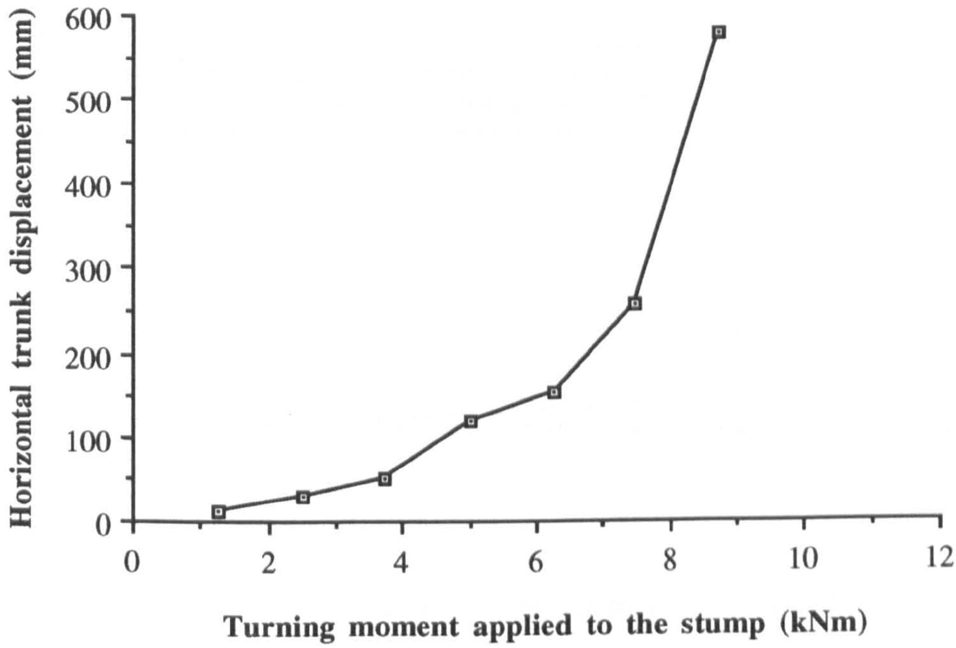


Figure 7.6 Trunk displacement during the uprooting of Acer 3

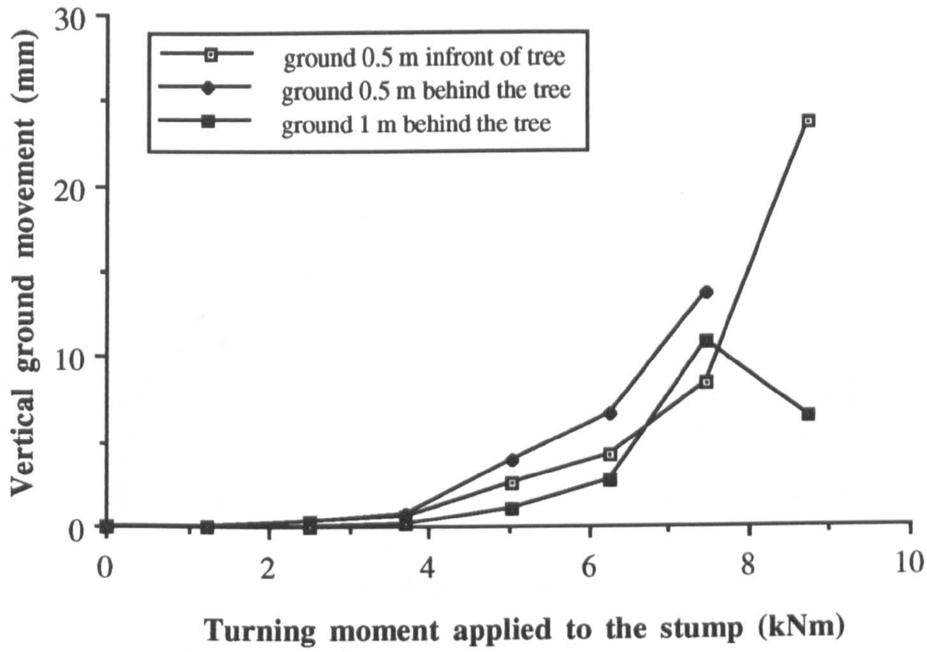


Figure 7.7a Ground movement during the uprooting of Acer 3

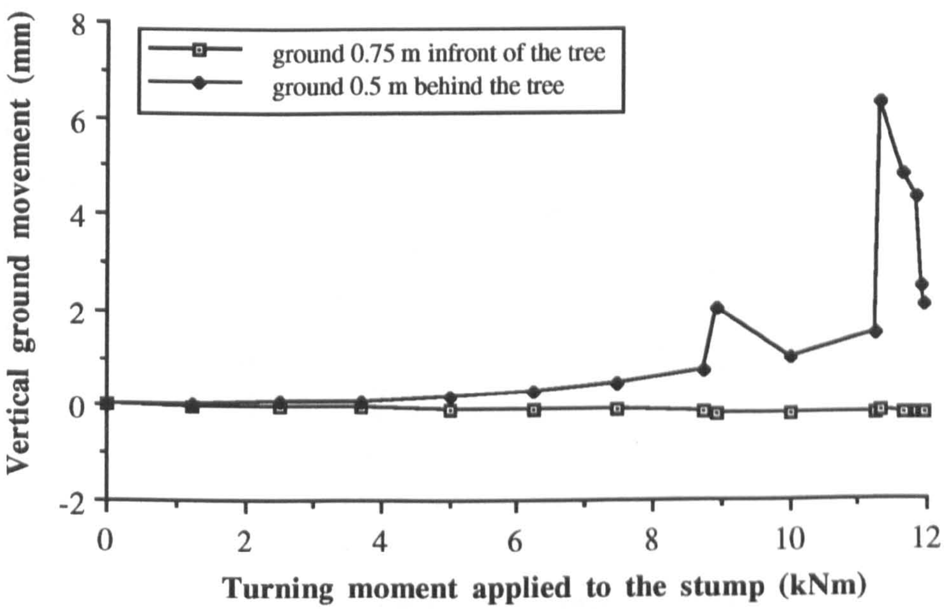
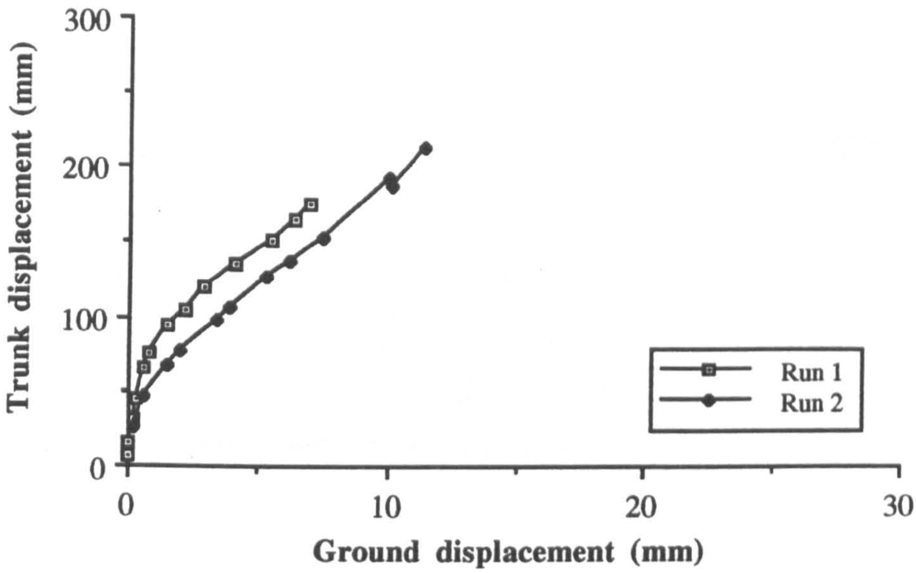
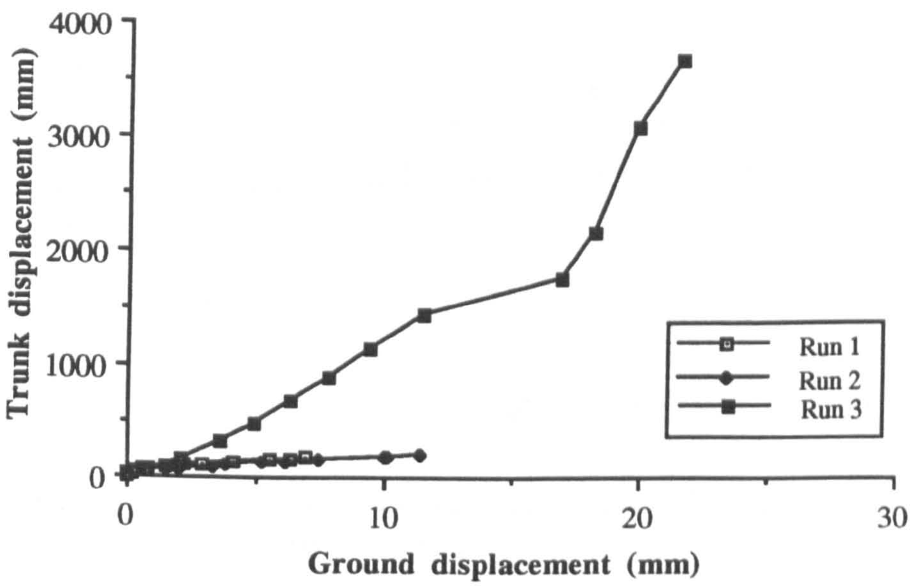


Figure 7.7b Ground movement during the uprooting of Acer 5
nb. depression of the ground infront of the tree



a) Close-up of loading runs 1 and 2



b) All 3 loading runs

Figure 7.8 Trunk displacement versus ground displacement - Acer 4

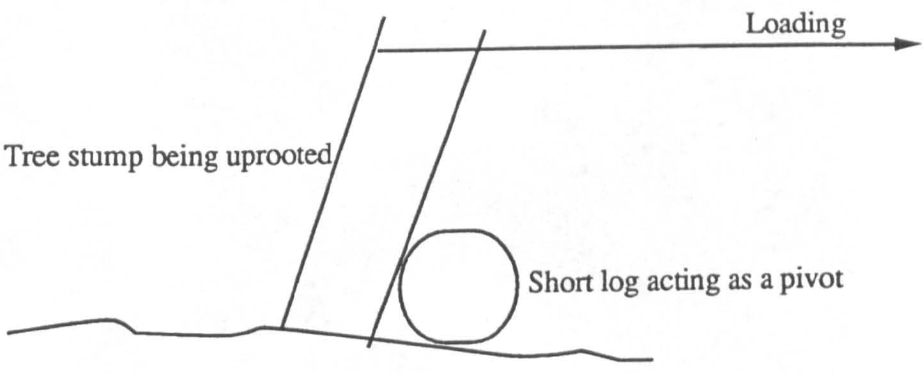


Figure 7.9 Uprooting with the aid of a pivot

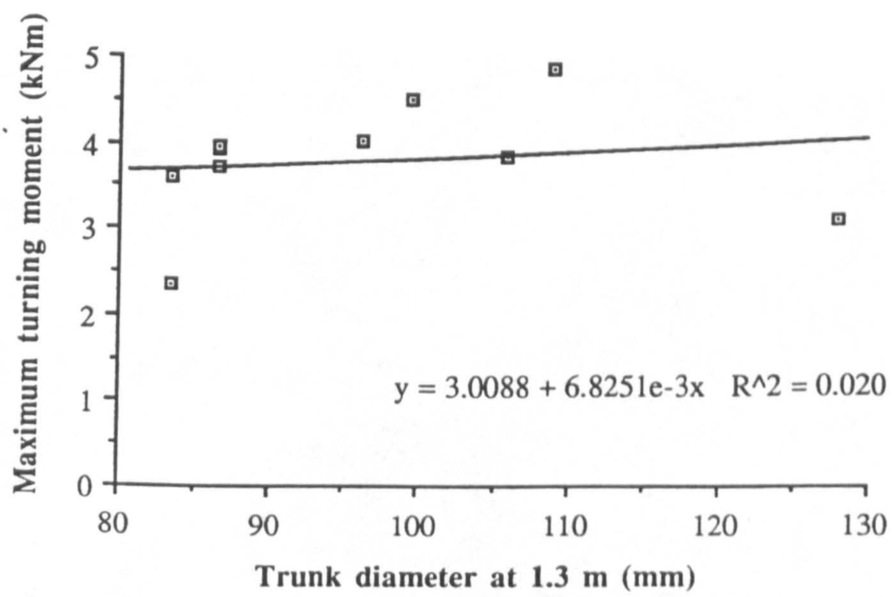


Figure 7.10 Maximum turning moments plotted against trunk diameter - Blidworth trees

Plate 7.1 - Tirfor winch with load cell monitoring system

Plate 7.2 - Strop and clamps attached to stump

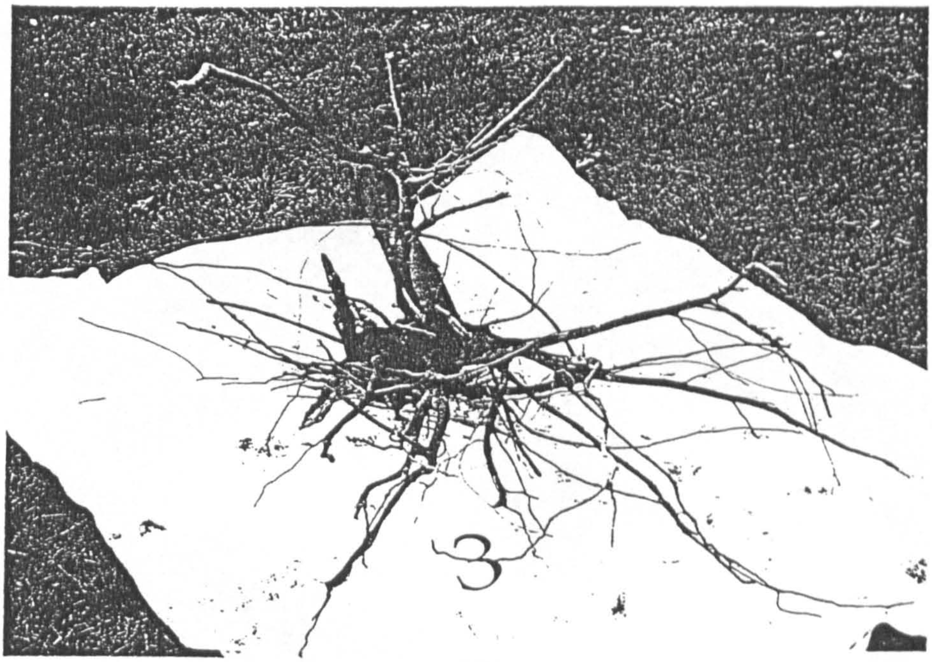


Plate 7.3 - Root system radiating laterally from the base of the stump at a shallow depth

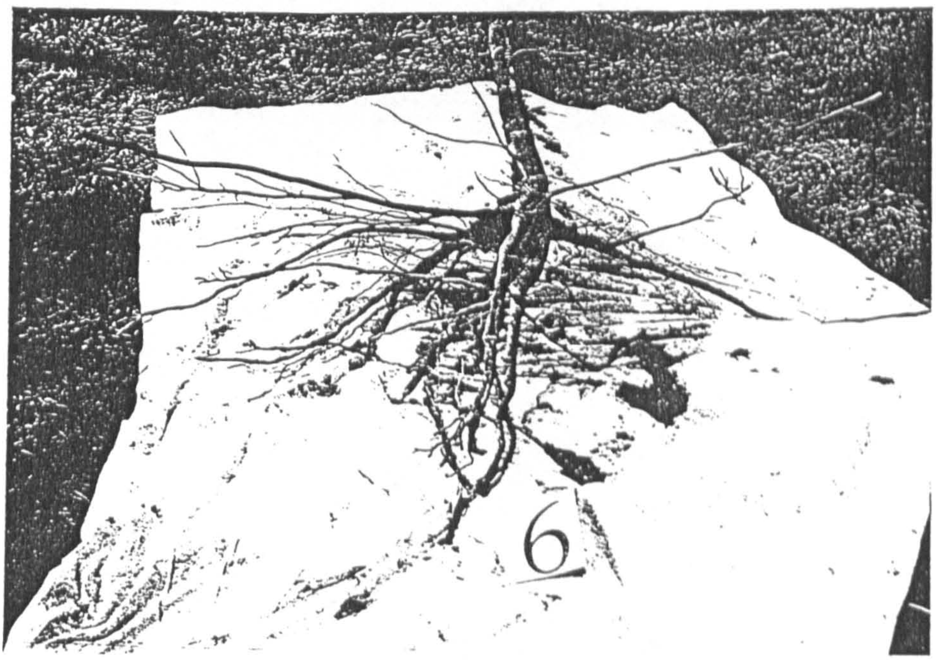


Plate 7.4 - Root system with no roots in the direction opposite to loading

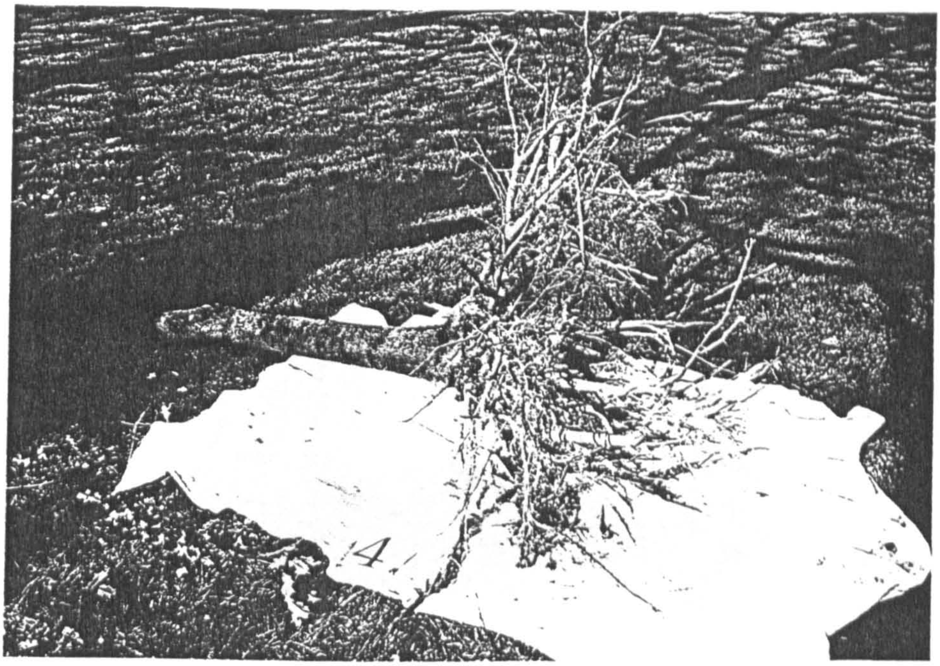


Plate 7.5 - Soil/ root-plate with protruding roots

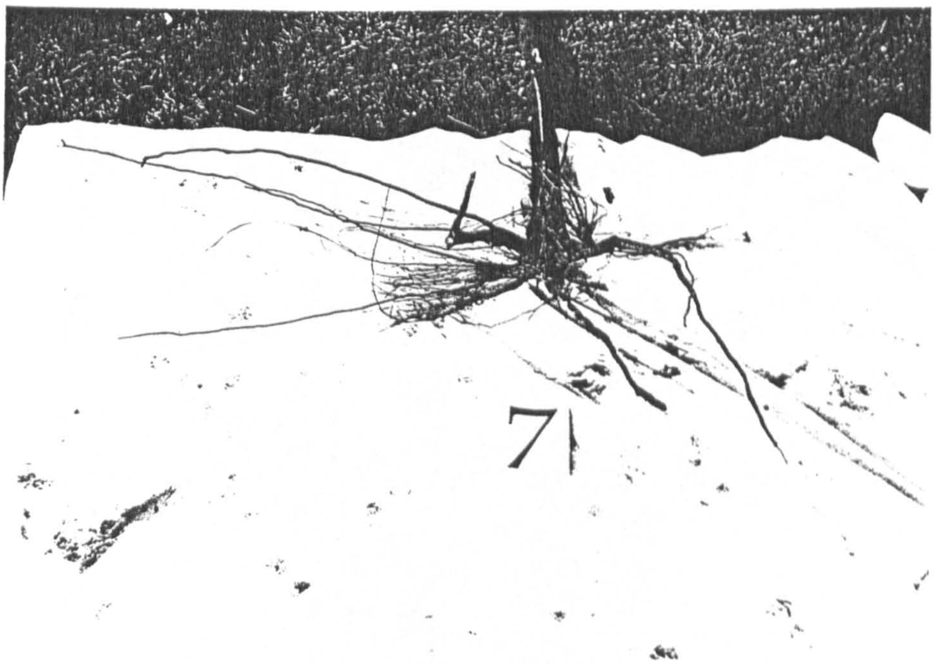


Plate 7.6 - Two tier root system

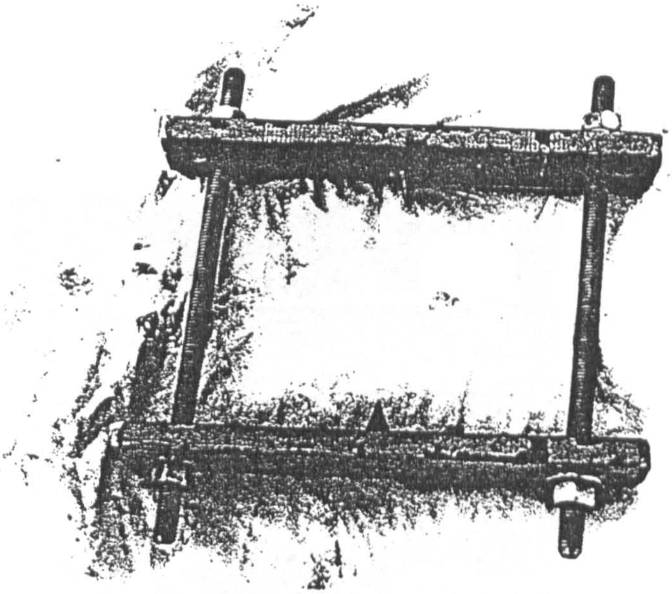


Plate 7.7 - Clamp designed to prevent strop slipping up trunk

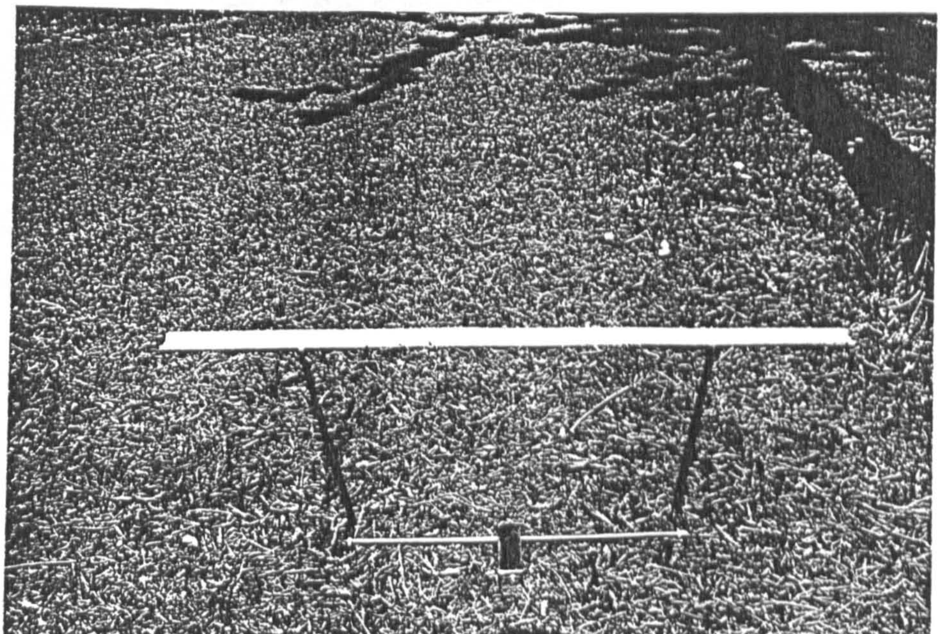


Plate 7.8 - Metre rule apparatus, to maintain horizontal positioning

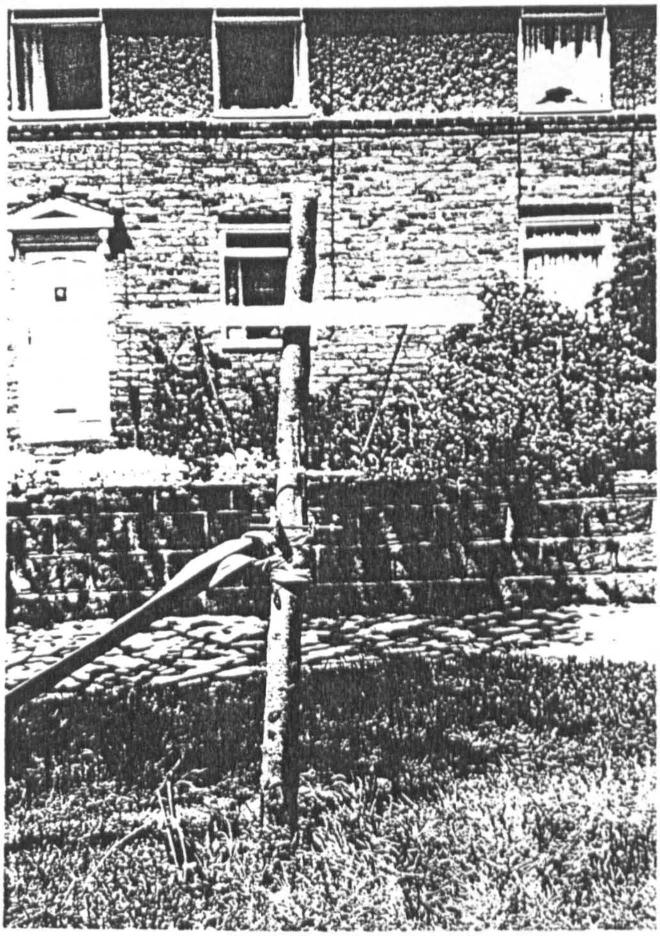


Plate 7.9 - Stump with metre rule and clamp

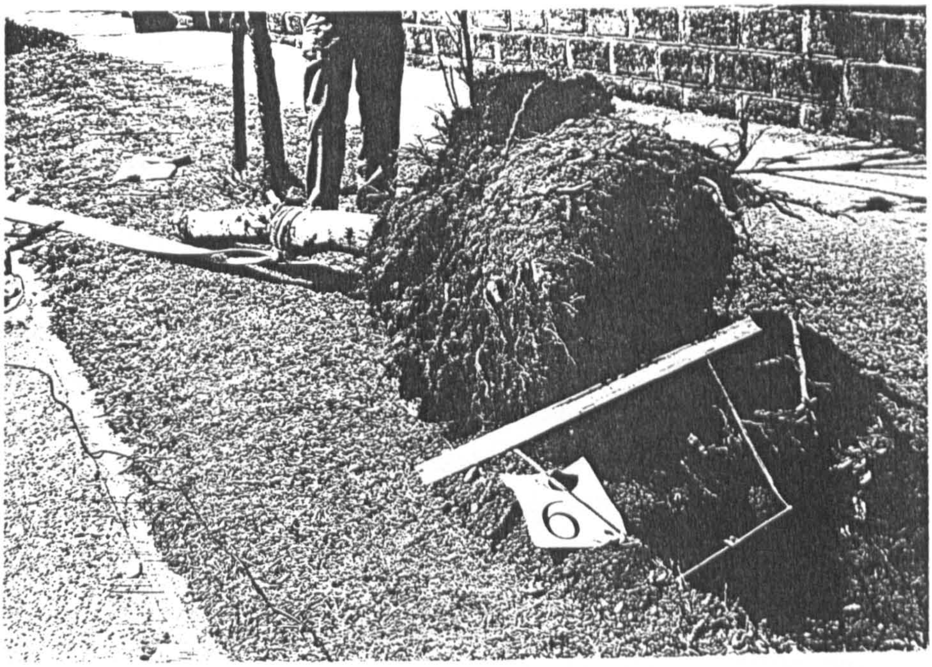


Plate 7.10 - Pit-bound root system

Plate 7.11 - Root system with soil removed

Chapter 8

Conclusions

8.0 Introduction

The literature review confirmed that tree stability is a complex issue, involving both the aerial and subterranean parts of the tree, and their interaction. It produced valuable information about the behaviour of coniferous species in windy conditions. However, it also revealed a relative lack of corresponding information on broadleaf trees, particularly those native to Britain. Indeed, unlike the coniferous trees, whose population and species can be estimated from the size and content of commercial plantations, there appeared to be very few records available for broadleaf trees.

This was an obvious area to direct research. A comprehensive database of trees and their physical parameters, both for fallen and standing trees, would enable tree stability in high winds to be further investigated. Though unavailable at the onset of this research at Nottingham University, such databases had been compiled by The Royal Botanic Gardens at Kew, the Forestry Commission, and Essex County Council following the 1987 storms. This data was later made available for analysis. Prior to the acquisition of these databases however, the author undertook a number of site visits following strong winds, to investigate the occurrence of wind damage to trees.

These site visits achieved their purpose and made the author more aware of the casualties arising from storm damage. In considering only the small number of trees surveyed it has become clear that tree fall is very complex. The occurrence and type of damage inflicted on the tree is not dependent on one, two or even three factors, but is a combination of many factors. These may be both external environmental influences and features intrinsic to each individual tree.

The conclusions drawn from all the surveys and databases are summarised in Section 8.1. Where possible, these conclusions were used in the selection of specimens for the practical experimentation (Chapters 5 and 6).

The literature described practical research on the stability of trees in plantations, related to spacing, root systems and soil types. Again coniferous trees were the subject of the research. Thus the research was projected towards similar experimentation with broadleaf trees. Before this experimentation commenced however, various results and observations, generated by the work with coniferous trees, were heeded. These included the limited use of static measurements in respect to tree fall in high winds, and also the difficulties involved in physically modelling individual trees for scaled down wind tunnel observation. It was decided that there was a need to carry out full scale observations of tree movement. These observations were to be made both in the wind, and by forced displacements, with the results being supported by static measurements.

The conclusions drawn from the experimental work are given in Section 8.2, with comparisons drawn with the results of the coniferous trees noted in the literature review.

Recommendations for further work form an important part of the conclusions, particularly due to the exploratory nature of the research. These are grouped together in Section 8.3.

8.1 The Survey Data

A large amount of useful information had been gathered in the form of the three databases (by the Royal Botanic Gardens at Kew, the Forestry Commission and by Essex County Council), each having specific advantages and disadvantages The databases were studied, compared and contrasted, and where possible conclusions drawn concerning tree species population, and various physical parameters of the trees related to wind damage.

(i) Species

Park lands were found to be comprised predominately of five genus (F.C. data):- *Acer*, *Aesculus*, *Fagus*, *Quercus*, and *Tilia*. Of these genus the *Acer* was seen to be the least susceptible to wind damage, though this may have been due to a bias towards a younger, and smaller population. *Fagus* and *Tilia* were found to be prone to uprooting in the wind, whilst *Aesculus* and *Quercus* appeared more prone to crown damage.

Of the more minor species, *Populus*, *Fraxinus*, *Carpinus* and *Cedrus* are most prone to crown damage, whereas *Platanus* and *Pinus* have a greater tendency to uproot. Of these genus, *Populus* and *Fraxinus* are the most likely to incur damage.

The particular fate of the tree was determined more by genus than size, though size was a factor, related to the genus, in whether the tree was damaged at all.

The composition of the population of trees growing in closer proximity to areas of greater public access (Kew and Essex data), consists of a wider range of tree species, with less dominance of any particular species. Exotic and ornamental species are planted for decoration and variety, often with a bias to the smaller growing species. *Malus*, *Prunus*, *Crataegus* and *Sorbus* are found to be the most commonly occurring genera of the smaller tree. Incidence of the uprooting or crown damage of these trees was not recorded in the surveys largely because of their absence in the F.C. survey. Investigation of their wind firmness is therefore inconclusive.

(ii) Tree's physical parameters

Trees of all sizes were seen to suffer crown damage and/ or uprooting in strong winds. However similar trees spanning all heights below 30 m were seen to remain unscathed in high winds. The differences between the number of trees in each height class was very little and unlikely to be significant with perhaps the exception of the trees over 30 m high. A greater tendency for trees of heights of 30 metre and above to fall, or at least receive crown damage was seen. The major genera all reflected these trends with trees present in each height class, and experiencing all the different fates. The greater proportion of small trees in the Essex data, and relative lack of these trees in the F.C. and Kew data suggested that the smaller tree was less susceptible to damage.

It therefore appears that tree height is not a critical factor in the survival of a tree in strong winds, with perhaps exceptions at the upper and lower extremities. The tallest trees over 30 m are found to be particularly vulnerable to wind damage, whilst the smallest trees, below 10 m, incur damage less frequently.

Tree size for any particular tree may be described in terms of height, as no significant or consistent differences were revealed between different genera in the relationship of height with either crown spread, or trunk diameter, with the exception of the F.C. fallen *Tilia*. Similarly differences in trees which fell and those which remained standing, or undamaged show no differences in physical structure other than general size, described as height in the previous paragraph.

The majority of the root plate were less than 4 metres in radius and less than 2 metres deep (Cutler, Gasson and Farmer, 1989, Gibbs and Greig 1990). (This information was not known at the onset of research at Nottingham, see Chapter 3 for details.)

(iii) Site Visits

The Site Visits survey compiled by the author was very small in comparison with the three other databases. However, valuable information was gained. The data collected compared well with that found by the larger surveys, but due to the small size of the database, closer attention to each specimen was possible. The survey showed tree failure by different means and in different situations to a number of species. An attempt was been made to determine why particular trees fail and others do not. The answers, though perhaps plausible, did not always give definitive reasons for each instance, they usually did not exclude the event of failure to the neighbouring undamaged tree, or the nearest tree of the same species.

Reasons suggested for tree failure include inhibited root growth, the location/ exposure of the tree and the presence of rot and decay.

Trees with root restrictions cannot establish laterals in all directions. Anchorage may therefore be less effective particularly if the windward roots are affected. Root restrictions may be caused by adverse ground conditions. These may be physical boundaries such as a wall or fence penetrating below ground level, soil compaction and consequent lack of water infiltration, water logging, or possibly the combination of both these factors.

Tree failure may be due to structural failure of the tree itself or by failure at the root-soil interface. Structural failure occurs if the wind incident on the tree causes sufficient stress in the trunk to make it snap, before the turning moment at the ground exceeds that necessary to uproot the tree. The presence of decay weakens the inherent strength of the tree, so it is not surprising that it is often found at the point of trunk breakage. Decay in the rooting system also reduces the tree's stability, though it does not necessarily determine the direction of fall. Decay was observed both on the windward side of the tree, and at 90° to the wind direction. It could be that trees with root decay on the leeward side withstood the storm, suggesting that these roots are less important in stability. Alternatively the decay may have passed unnoticed if it were buried in the soil. As the uprooting process is currently thought to be a dynamic process caused by winds gusting and trees rocking it would seem that the leeward roots must be of some importance in stability, though not necessarily the major factor.

Observations of the root-plates suggest that, generally, they are shallow, with lateral roots radiating from the trunk. This was seen in all the soil types, though perhaps the roots were a little shallower on the shale and thinner soils at Saltram House. The development of this rooting system remains a mystery. The sapling tree has a tap root which at some stage dies back and is replaced by these laterals.

The Site Visits also enabled the following conclusions to be drawn about the surveying of trees.

In any survey the degree of accuracy gained should not outweigh the usefulness of the survey. However the validity of any survey is only as good as the information entered. A survey must be carefully researched, to encompass as many variations as possible, whilst not being so extensive and complex that the results cannot be analysed, or with insignificant repetitions to make the data statistically invalid. Definitions of the parameters must be very specific in order to minimise differing interpretation which may be adopted if the survey is to be carried out by independent bodies.

8.2 Experimental Work

(i) Wind characteristics and resulting tree movement

Higher wind speeds were recorded in the periods when the *Platanus* was out of leaf, i.e. the winter. It was also noted that in the winter the wind was found to have more energy at the higher frequency range than it did in the summer recording sessions.

The tree was however seen to deflect more in lower wind speeds when it had leaves, than in the higher wind speeds when it was without leaf.

The tree without leaves was found to have a higher natural frequency of oscillation with a much lower damping ratio than the tree with leaves.

The tree deflection/ wind ratio, natural frequency of oscillation and damping coefficients are related.

It may be hypothesised that the tree has developed the ability to vary such parameters as a defence mechanism for survival from windblow. Were the tree to maintain its high deflection to wind ratio in the winter when stronger winds were expected, damage would most probably ensue. Also, and not unrelated, if the natural frequency of oscillation of the tree, were to remain at the lower frequency values, recorded whilst it had leaves on, the increased energy of the wind at these frequencies in the higher winds, would again increase the likelihood of failure.

(ii) Forced oscillation and static loading

The displacement/ load ratio does not vary greatly between season. The results suggest that this ratio decreases as the trunk diameter increases.

The forced oscillation experiments confirmed the following findings of the wind induced tree movement observations :- the tree has a lower natural frequency of oscillation when it is in leaf, and the damping ratio in higher for a tree in leaf.

The drag coefficient of a tree is much higher when it is in leaf, than when it has no leaves.

The drag coefficient of the *Platanus,* whilst in full leaf, was within the range determined by Mayhead (1973a), suggesting that broadleaf trees have similar drag coefficients to conifers. However the hypothesis proposed by Fraser (1962) and Mayhead (1973a), of the drag being proportional to velocity, as opposed to velocity squared was not confirmed.

(iii) Tree uprooting

Considering the size of trees uprooted by Fraser (1962), the campus *Acer*s, and the Blidworth trees it can be concluded that larger trees require greater turning moments to uproot them.

Trees planted with restricted roots, either by drainage problems, as seen in the surveys, or by physical boundaries such as being pit-bound, will develop an inferior root system which makes the tree less stable to uprooting forces. The ground movement observed to occur by pit-bound trees was greater than by the self-seeded or well-planted trees, both for loading applied to the tree's crown and at the base of the tree.

Tree winching with the load applied close to the base of the trunk, does not adequately simulate wind effects, as much greater horizontal shear forces at the ground level are produced. Uprooting values calculated from such experiments cannot therefore be used directly to estimate the wind speeds which would cause uprooting. However, these values will indicate the relative stability of trees, and with further research the relationship between the two values perhaps modelled.

The ratio of turning moment/ trunk displacement at the initial loading values, before the elastic limit is exceeded, indicates the turning moment at uprooting. This could be a very useful observation in assessing the strength of the tree's root system, particularly as it could be carried out without damaging the tree's root/ soil system. As yet it is only a relative factor, but with further research this too could be incorporated into a model to predict the wind speeds that cause uprooting.

8.3 Further work recommendations

An increase in the tree database would always be beneficial, though, greater accuracy would be useful in future surveys. Even then the accuracy would not be that required of an experiment run in controlled conditions with specific numbers of repetitions and controlled variables.

Further work is required in relating to the soil types, associated tree population and wind damage. This would clarify the findings of the Kew and F.C. surveys, for instance whether sandy soils provided a less stable soil than brown earths. It would be most useful if it could be carried out on a local scale to account for specific variations in the climate, aspect and underlying bedrock. It should also take into account the particular tree species which are grown extensively on any particular soil type and whether any apparent variation in tree stability is in fact due more to the tree species than the soil type.

The research reported in this thesis formed a pilot study for research into the dynamics and aerodynamics of urban trees. It is therefore expected that further research would repeat the experimental procedures developed in this research on many more trees, ideally for both the monitoring of trees in the wind and the forced oscillation experiments. Further work could repeat the experiments on trees of the same species but of different age and size. This would confirm whether the displacement/ load ratio decreases as the trunk diameter increases. The response of other species would also be valuable to assess the variation between them and produce drag coefficient scale for broadleaf trees, comparable to that produced by Mayhead (1973a) for conifers.

It was noted that the load applied to the tree during the oscillation experiments was applied at an angle (Fig. 6.1). The horizontal force was thus calculated using the cosine of the pulling angle. The vertical component of this loading would be acting downwards along the axis of the tree. The influence of this vertical force on the behaviour of the tree is unknown and requires further investigation.

Mathematical modelling may be employed in the future to develop and investigate trends in the behaviour of particular aspects of the mechanics involved in tree stability. For this purpose the thesis includes tabulated values of trunk displacement with applied moment over the elastic range (Tables 7.5 and 7.9), and detailed profiles of partially uprooted trees (Fig 4.5, Table 4.1).

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Appendix A

Tables of Regression Values

Table 1 The regression values for the Survey data discussed in Chapter 3
Table 2 The regression values for the author's survey data discussed in Chapter 4

Quantitative Notation:

X	mean value of data set
se	standard error of data set
n	number of values in the data set
inter	value of intercept when regression line is projected on a graph
V%	variance accounted for as a percentage
T	t-test value
DF	degrees of freedom for use in t-test

The values of T and DF are only given in Table 2. These refer to the comparisons of data sets listed directly below each other, for example, when comparing the trunk diameter versus crown spread regressions of a) all the FC trees, and b) all the trees in the author's survey. Due to the number and complexity of the comparisons made in Chapter 3 the results could not be presented in this form, and are given in the Tables associated with Chapter 3.

Descriptive Notation:

U	undamaged trees
F	fallen trees
CD	crown damaged trees
Crnspd	crown spread of tree
Dbh	trunk diameter
Root diam	root-plate diameter

	x	se	n	inter	% V
Dbh v Crnspd					
Essex school	4.5884	0.0323	12858	-2.345	60.8
Essex street	4.9204	0.0901	2113	-0.274	58.5
Essex other site	5.115	0.124	1292	-2.483	56.8
Sorbus	3.0315	0.054	1598	1.058	66.3
Prunus	1.9674	0.043	3608	5.703	36.7
Malus	2.4942	0.0625	1893	3.919	45.7
FC All -U	3.6081	0.0839	2490	20.99	42.6
FC All -F	4.864	0.321	271	17.09	45.7
FC All -CD	4.296	0.243	501	29.14	38.2
FC Quercus -U	3.831	0.198	528	16.67	41.3
FC Quercus -F	3.147	0.513	55	36.85	39.6
FC Quercus -CD	2.787	0.44	179	61.94	17.8
FC Fagus -U	3.954	0.239	318	8.49	46.1
FC Fagus -F	5.061	0.57	43	19.28	
FC Fagus -CD	3.647	0.744	48	42.4	31.9
FC Tilia -U	4.401	0.202	666	13.78	41.6
FC Tilia -F	6.994	0.672	114	-4.23	48.3
FC Tilia -CD	4.987	0.951	58	25.2	31
FC Aesculus -U	3.73	0.225	323	18.79	45.7
FC Aesculus -F	3.62	1.06	7	10.6	56.9
FC Aesculus -CD	3.709	0.493	110	29.37	33.4
Kew All -F	4.151	0.304	307	22.67	37.6
Kew All -CD	4.86	2.57	9	24.7	20.5
Kew Quercus -F	3.781	0.527	105	27.82	32.3
Kew Tilia -F	2.65	1.81	15	55.4	6.6
Kew Fagus -F	3.837	0.649	73	32.4	31.5
Kew Aesculus -F	14	19.1	2	-56	exceeded
FC Quercus robur	3.559	0.546	68	26.27	37.6
FC Fagus sylvatica	3.837	0.649	73	32.4	31.5
FC Cedrus -F	12.67	2.68	5	-84.4	78.1
FC Pinus -F	5.28	1.56	10	16.92	48.8
FC Cedrus -U	4.188	0.355	100	13.14	57.8
FC Pinus -U	3.785	0.389	104	21.71	47.1
FC Cedrus -CD	5.87	2.39	10	37.4	31.4
FC Pinus -CD	4.48	3.44	4	17.4	12.3

Table A1 Regression table of data from F.C., Kew and Essex surveys

	x	se	n	inter	% V
Height v Dbh					
FC All -CD	0.09323	0.00607	513	12.499	31.4
FC All -U	0.08261	0.00298	2490	14.61	23.5
FC All -F	0.12275	0.00868	340	12.955	36.8
FC Cedrus -F	-0.0189	0.0344	8	23.82	exceeded
FC Pinus -F	0.2684	0.05	10	4.28	71.7
FC Cedrus -U	0.08315	0.00986	100	13.5	41
FC Pinus -U	0.0812	0.0174	104	16.75	16.5
FC Cedrus -CD	0.0565	0.0159	11	12.46	49.4
FC Pinus -CD	0.209	0.0666	5	5.43	59.6
Kew Aesculus -F	0.0239	0.0602	2	11.61	exceeded
Kew Fagus -F	0.046	0.0158	88	19.11	7.8
Kew Tilia -F	0.1785	0.0422	21	6.19	43.4
Kew Quercus -F	0.0598	0.0113	129	14.275	17.2
Kew All -F	0.07111	0.00764	371	14.811	18.7
Kew All -CD	0.0692	0.0204	11	9.82	46.7
Root diam v depth					
FC Quercus -F	0.481	0.278	59	2.371	3.2
FC Tilia -F	2.363	0.305	140	1.536	29.5
FC Aesculus -F	1.368	0.806	11	1.466	13.6
FC Fagus -F	2.006	0.621	64	2.765	12.7
FC Pinus -F	0.241	0.447	9	2.379	exceeded
FC Cedrus -F	-2.48	1.37	8	6.03	20.3
Root diam v Dbh					
FC Quercus -F	16.94	3.03	59	31.31	33.6
FC Tilia -F	17.13	1.21	147	16.14	57.3
FC Aesculus -F	6.47	3.61	12	37.93	14.5
FC Fagus -F	12.4	1.75	63	34.33	43.6
FC Pinus -F	17.33	7.02	9	-0.7	33.8
FC Cedrus -F	2.7	11.5	8	100.8	exceeded

Table A1(cont.) Regression table of data from F.C., Kew and Essex surveys

	x	se	n	inter	% v	T	DF
Dbh v Crnspd							
FC ALL	4.864	0.321	271	17.09		**0.81**	**45.80**
All	3.92	1.04	27	36.1	32.3	**-0.23**	**9.56**
Aberdeen	4.31	1.78	4	35.6	49.2	**0.20**	**11.26**
Not Aberdeen	3.96	1.37	21	34.9	25		
FC Quercus	3.147	0.513	55	36.85		**-1.68**	**-0.27**
Quercus	6.13	2.63	7	1.5	35.7	**0.14**	**0.25**
Fagus	5.83	1.66	8	23.5	55.7	**1.16**	**18.96**
FC Fagus	5.061	0.57	43	19.28	7.62		
All	3.92	1.04	27	36.1		**-0.24**	**9.17**
Standing	4.34	1.9	4	38.4	45.7	**0.52**	**4.36**
FC -U	3.6081	0.0839	2490	20.99			
Height v Crnspd							
FC -F	0.12275	0.00868	340	12.955	0.692	**-0.43**	**30.00**
All	0.3	0.16	27	13.1	8.3	**-0.17**	**7.60**
Aberdeen	0.431	0.406	4	10.06	2.5	**0.36**	**8.32**
Not Aberdeen	0.155	0.192	21	15.52	exceeded		
Quercus	0.654	0.198	7	6.49	55.4	**-0.15**	**14.09**
Fagus	0.77	0.384	8	11.04	25.2		
All	0.3	0.16	27	13.1		**0.41**	**7.80**
Standing	-0.003	0.386	4	20.37		**-0.14**	**4.06**
FC -U	0.08261	0.00298	2490	14.61			
Dbh v Root diam							
All	15.16	5.54	31	27.1	16.9	**-0.61**	**64.11**
FC Quercus	16.94	3.03	59	31.31		**-5.51**	**10.18**
Quercus	40	14.5	7	-56	45.3	**5.50**	**12.98**
Fagus	14.93	6.3	12	23.3	26.2	**0.89**	**19.31**
FC Fagus	12.4	1.75	63	34.33			
Root diam v Depth							
All	-1.046	0.464	29	4.628	12	**-1.77**	**63.04**
FC Quercus	0.481	0.278	59	2.371		**-0.05**	**2.59**
Quercus	0.56	2	2	4.5		**0.47**	**4.55**
Fagus	-0.27	1.09	12	4.076	exceeded	**-1.74**	**27.87**
FC Fagus	2.006	0.621	64	2.765			
Height v Dbh							
All trees	0.0911	0.0166	35	9.24	44.6	**-0.12**	**24.99**
Aberdeen	0.1163	0.0283	11	6.31	56.9	**0.18**	**25.96**
Not Aberdeen	0.0772	0.0206	22	11.07	36.1		

Table A2 Regression table of data from author's surveys

Appendix B

Survey Sheets

of trees in Aberdeen, and SW England

APPENDIX B

Tree Survey Sheet

Site	:	Aberdeen
Tree number	:	1
Species	:	Beech *(Fagus)*
Location - street/park/hedgerow	:	School ground - row of Beech
Surrounding ground	:	Grass - slightly sloping
Height (m)	:	15 - 17m
Maximum diameter at 1m (cm)	:	65cm
Crown spread - open/dense	:	Open
Asymmetrical growth	:	In group - 1 sided
Pollarded?	:	No
Age - Y, SM, M	:	M
Disease?	:	No
Physical damage to roots	:	No
Root plate: -		
Diameter (m)	:	3m
Thickness at centre (cm)	:	50cm
Depth of hole (m)	:	1m
Thickness of roots at snapping point (cm)	:	6cm - windward side, 0.5-1cm
Soil description	:	Soft, brown, silty clay with small stones
Soil moisture content	:	0.26 on root-plate, 0.175 on edge of hole
		Surface soil sample had many very thin fibrous rootlets (gross). 8cm top soil before any tree roots.

APPENDIX B

Tree Survey Sheet

Site	:	Aberdeen
Tree number	:	2
Species	:	Beech *(Fagus)*
Location - street/park/hedgerow	:	School ground - row of Beech
Surrounding ground	:	Grass - slightly sloping
Height (m)	:	15 - 17m
Maximum diameter at 1m (cm)	:	65cm
Crown spread - open/dense	:	Open
Asymmetrical growth	:	In group - 1 sided
Pollarded?	:	No
Age - Y, SM, M	:	M
Disease?	:	No
Physical damage to roots	:	No
Root plate: -		
Diameter (m)	:	3m
Thickness at centre (cm)	:	60cm
Depth of hole (m)	:	60cm - rock below
Thickness of roots at snapping point (cm)	:	10cm
Soil description	:	Soft, brown,silty clay with small stones
Soil moisture content	:	0.28

APPENDIX B

Tree Survey Sheet

Site	:	Aberdeen
Tree number	:	3
Species	:	Lime *(Tilia)*
Location - street/park/hedgerow	:	Park
Surrounding ground	:	Grass
Height (m)	:	11m
Maximum diameter at 1m (cm)	:	60cm
Crown spread - open/dense	:	6m
Asymmetrical growth	:	No
Pollarded?	:	No
Age - Y, SM, M	:	M
Disease?	:	Yes - Honey Fungus
Physical damage to roots	:	-
Root plate: -		
Diameter (m)	:	
Thickness at centre (cm)	:	Roots not seen, snapped at base
Depth of hole (m)	:	
Thickness of roots at snapping point (cm)	:	-
Soil description	:	-
Soil moisture content	:	-

APPENDIX B

Tree Survey Sheet

Site	:	Aberdeen
Tree number	:	4
Species	:	Beech *(Fagus)*
Location - street/park/hedgerow	:	Roadside
Surrounding ground	:	Grass
Height (m)	:	13m
Maximum diameter at 1m (cm)	:	65cm
Crown spread - open/dense	:	Open
Asymmetrical growth	:	No
Pollarded?	:	No
Age - Y, SM, M	:	M
Disease?	:	Yes - Honey Fungus
Physical damage to roots	:	No
Root plate: -		
Diameter (m)	:	2.5m
Thickness at centre (cm)	:	60cm
Depth of hole (m)	:	1m
Thickness of roots at snapping point (cm)	:	10cm
Soil description	:	Soft, well aggregated brown earth (loam)
Soil moisture content	:	0.24 below roots. 0.22 bottom of root-plate

Soil below roots dense and more compacted than on root-plate.

Roots very one sided all broken - rotten.

APPENDIX B

Tree Survey Sheet

Site	:	Aberdeen
Tree number	:	5
Species	:	Elm *(Ulmus)*
Location - street/park/hedgerow	:	Park
Surrounding ground	:	Grass
Height (m)	:	14m
Maximum diameter at 1m (cm)	:	75cm
Crown spread - open/dense	:	8m
Asymmetrical growth	:	Yes
Pollarded?	:	No - but heavily pruned up stem
Age - Y, SM, M	:	M
Disease?	:	Yes - Rotted at base
Physical damage to roots	:	-
Root plate: -		
Diameter (m)	:	3m
Thickness at centre (cm)	:	65cm
Depth of hole (m)	:	0.5m
Thickness of roots at snapping point (cm)	:	Base of tree
Soil description	:	Soft, sandy loam with small stones
Soil moisture content	:	0.315

NB. Rot on one side - twisted at root. Roots (healthy) very fibrous.

APPENDIX B

Tree Survey Sheet

Site	:	Aberdeen
Tree number	:	6
Species	:	Elm *(Ulmus)*
Location - street/park/hedgerow	:	Park
Surrounding ground	:	Ground and bituminous macadem on two sides
Height (m)	:	15m
Maximum diameter at 1m (cm)	:	1m
Crown spread - open/dense	:	18m dense/many branches
Asymmetrical growth	:	No
Pollarded?	:	No
Age - Y, SM, M	:	M
Disease?	:	-
Physical damage to roots	:	Yes. Confirmed - compacted and severed
Root plate: -		
Diameter (m)	:	1.5m
Thickness at centre (cm)	:	1m
Depth of hole (m)	:	0.3m
Thickness of roots at snapping point (cm)	:	40cm (rotten deep root), side roots 15-16cm
Soil description	:	Soft, sandy brown loam with small stones
Soil moisture content	:	0.14
		NB. May have had extra soil added to top

APPENDIX B

Tree Survey Sheet

Site	:	Aberdeen
Tree number	:	7
Species	:	Beech (2 trees) *(Fagus)*
Location - street/park/hedgerow	:	Roadside
Surrounding ground	:	Grass, ditch and wall
Height (m)	:	18m
Maximum diameter at 1m (cm)	:	85cm
Crown spread - open/dense	:	8m + 6m
Asymmetrical growth	:	Crowns together
Pollarded?	:	No
Age - Y, SM, M	:	M
Disease?	:	No
Physical damage to roots	:	Confined by ditch and wall
Root plate: -		
Diameter (m)	:	6m (2 together)
Thickness at centre (cm)	:	1m
Depth of hole (m)	:	1m
Thickness of roots at snapping point (cm)	:	12cm, 18cm
Soil description	:	Yellow/brown sand with very small stones
Soil moisture content	:	0.09 (dry!)
		Wall on windward side

APPENDIX B

Tree Survey Sheet

Site	:	Aberdeen
Tree number	:	8
Species	:	Beech *(Fagus)*
Location - street/park/hedgerow	:	Park
Surrounding ground	:	Grass
Height (m)	:	5m
Maximum diameter at 1m (cm)	:	15cm
Crown spread - open/dense	:	1.5m
Asymmetrical growth	:	No
Pollarded?	:	No
Age - Y, SM, M	:	Y
Disease?	:	No
Physical damage to roots	:	No
Root plate: -		
Diameter (m)	:	
Thickness at centre (cm)	:	Not uprooted. Main windward root broken.
Depth of hole (m)	:	Growing at angle.
Thickness of roots at snapping point (cm)	:	-
Soil description	:	-
Soil moisture content	:	-

APPENDIX B

Tree Survey Sheet

Site	:	Aberdeen
Tree number	:	9
Species	:	Elm *(Ulmus)*
Location - street/park/hedgerow	:	Park
Surrounding ground	:	Daffodils - Primroses
Height (m)	:	18m
Maximum diameter at 1m (cm)	:	70cm
Crown spread - open/dense	:	Dense
Asymmetrical growth	:	No
Pollarded?	:	No
Age - Y, SM, M	:	M
Disease?	:	No
Physical damage to roots	:	No
Root plate: -		
Diameter (m)	:	3m
Thickness at centre (cm)	:	50cm
Depth of hole (m)	:	2m
Thickness of roots at snapping point (cm)	:	Maximum 5cm but generally did not snap
Soil description	:	Slightly sandy, brown earth
Soil moisture content	:	Very wet
		Twin forked - tree resting on lower branch

APPENDIX B

Tree Survey Sheet

Site	:	Aberdeen
Tree number	:	10
Species	:	Beech *(Fagus)*
Location - street/park/hedgerow	:	Park
Surrounding ground	:	Grassy slope - fell uphill
Height (m)	:	15m
Maximum diameter at 1m (cm)	:	55cm
Crown spread - open/dense	:	Open
Asymmetrical growth	:	No
Pollarded?	:	No
Age - Y, SM, M	:	M
Disease?	:	No
Physical damage to roots	:	No
Root plate: -		
Diameter (m)	:	3.5m long root
Thickness at centre (cm)	:	30cm
Depth of hole (m)	:	0.5m
Thickness of roots at snapping point (cm)	:	4cm maximum
Soil description	:	Sandy loam
Soil moisture content	:	Dry

APPENDIX B

Tree Survey Sheet

Site	:	Aberdeen
Tree number	:	11
Species	:	Beech *(Fagus)*
Location - street/park/hedgerow	:	Park
Surrounding ground	:	Daffodils - slope - fell downhill
Height (m)	:	18m
Maximum diameter at 1m (cm)	:	120cm
Crown spread - open/dense	:	Dense
Asymmetrical growth	:	No
Pollarded?	:	No
Age - Y, SM, M	:	M
Disease?	:	No
Physical damage to roots	:	No
Root plate: -		
Diameter (m)	:	3m
Thickness at centre (cm)	:	1m
Depth of hole (m)	:	60cm (fulcrum - trunk base)
Thickness of roots at snapping point (cm)	:	8-9cm, windward. Larger perpendiculars to tree fall torn
Soil description	:	Granular - Sandy, large grains
Soil moisture content	:	Dry

APPENDIX B

Tree Survey Sheet

Site	:	Aberdeen
Tree number	:	12
Species	:	Elm *(Ulmus)*
Location - street/park/hedgerow	:	Park
Surrounding ground	:	Grass
Height (m)	:	12m
Maximum diameter at 1m (cm)	:	60cm
Crown spread - open/dense	:	Narrow
Asymmetrical growth	:	No
Pollarded?	:	No
Age - Y, SM, M	:	M
Disease?	:	Yes
Physical damage to roots	:	No
Root plate: -		
Diameter (m)	:	Snapped at 2m height
Thickness at centre (cm)	:	Roots firmly in ground
Depth of hole (m)	:	
Thickness of roots at snapping point (cm)	:	-
Soil description	:	-
Soil moisture content	:	-

TREE SURVEY SHEETS FROM THE SOUTH OF ENGLAND
25th January 1990

Tree Number	: 1
Site	: Killerton
Species	: Holm Oak (*Quercus ilex*)
Location - Street/Park/Hedgerow	: Park
Height (m)	: 14.5
Crown Spread (m)	: 17
Height to Crown (m)	: 2
Trunk Diameter (Dbh) (cm)	: 17
Disease/Decay	: None
Physical Damage to Roots	: None
Root-Plate:-	
Maximum Depth of Roots (m)	: 1.1
Depth Containing Major Laterals (cm)	: 60-80
Depth of Soil Above Roots (cm)	: 0
Horizontal Root Plate Diameter (m)	: 3.1
Horizontal Roots Protruding (m)	: 1.5
Vertical Root Plate Radius (m)	: 1.75
Vertical Roots Protruding (m)	: 0.75
Thickness of Roots at Snapping Point (mm)	: 5, 6, 10, 14, 15, 17, 18, 19, 21, 40, 70, 80, 90
Soil Description	: Red/brown soft/ firm very clayey silt with occasional packets of sand
Other Comments	:

TREE SURVEY SHEETS FROM THE SOUTH OF ENGLAND
25th January 1990

Tree Number	: 2
Site	: Killerton
Species	: Atlantic Cedar (*Cedrus atlantica*)
Location - Street/Park/Hedgerow	: Park
Height (m)	:
Crown Spread (m)	:
Height to Crown (m)	:
Trunk Diameter (Dbh) (cm)	:
Disease/Decay	:
Physical Damage to Roots	:
Root-Plate:-	
Maximum Depth of Roots (m)	:
Depth Containing Major Laterals (cm)	:
Depth of Soil Above Roots (cm)	:
Horizontal Root Plate Diameter (m)	:
Horizontal Roots Protruding (m)	:
Vertical Root Plate Radius (m)	:
Vertical Roots Protruding (m)	:
Thickness of Roots at Snapping Point (mm)	:
Soil Description	:
Other Comments	:

TREE SURVEY SHEETS FROM THE SOUTH OF ENGLAND
25th January 1990

Tree Number	: 3
Site	: Killerton
Species	: Holm Oak (*Quercus ilex*)
Location - Street/Park/Hedgerow	: Park
Height (m)	: 12
Crown Spread (m)	: 20
Height to Crown (m)	: 2
Trunk Diameter (Dbh) (cm)	: 120
Disease/Decay	:
Physical Damage to Roots	:
Root-Plate:-	
Maximum Depth of Roots (m)	:
Depth Containing Major Laterals (cm)	:
Depth of Soil Above Roots (cm)	:
Horizontal Root Plate Diameter (m)	:
Horizontal Roots Protruding (m)	:
Vertical Root Plate Radius (m)	:
Vertical Roots Protruding (m)	:
Thickness of Roots at Snapping Point (mm)	:
Soil Description	:
Other Comments	: Slightly sheltered on one side. Ground higher and drier on a slight slope

TREE SURVEY SHEETS FROM THE SOUTH OF ENGLAND
25th January 1990

Tree Number	: 4
Site	: Killerton
Species	: Holm Oak (*Quercus ilex*)
Location - Street/Park/Hedgerow	: Park
Height (m)	: 12
Crown Spread (m)	: 15
Height to Crown (m)	: 1.7
Trunk Diameter (Dbh) (cm)	: 65
Disease/Decay	: None
Physical Damage to Roots	: None
Root-Plate:-	
Maximum Depth of Roots (m)	: 0.80
Depth Containing Major Laterals (cm)	: -
Depth of Soil Above Roots (cm)	: 15
Horizontal Root Plate Diameter (m)	: 3.5
Horizontal Roots Protruding (m)	: 5
Vertical Root Plate Radius (m)	: 1.75
Vertical Roots Protruding (m)	: 0.55
Thickness of Roots at Snapping Point (mm)	: 6, 7, 8, 8, 9, 9, 9, 10, 13, 13, 18, 19, 20, 21
Soil Description	: Red/brown silt. Many angular stones
Other Comments	: Very flat soil-root ball, peripheral ground heave. 2 Sweet Chestnuts 5 m up wind. Fulcrum 0.7 m, i.e. root drop on lee side by 0.7 m

TREE SURVEY SHEETS FROM THE SOUTH OF ENGLAND
25th January 1990

Tree Number	: 5
Site	: Killerton
Species	: Holm Oak (*Quercus ilex*)
Location - Street/Park/Hedgerow	: Park
Height (m)	: 10
Crown Spread (m)	: 9
Height to Crown (m)	: 1.5
Trunk Diameter (Dbh) (cm)	: 75
Disease/Decay	: None
Physical Damage to Roots	: None
Root-Plate:-	
Maximum Depth of Roots (m)	: 0.8
Depth Containing Major Laterals (cm)	: 50
Depth of Soil Above Roots (cm)	: 12
Horizontal Root Plate Diameter (m)	: 3.5
Horizontal Roots Protruding (m)	: 0.5
Vertical Root Plate Radius (m)	: 1.4
Vertical Roots Protruding (m)	: 0.6
Thickness of Roots at Snapping Point (mm)	: 4, 4, 6, 6, 7, 7, 7, 7, 9, 12, 14, 16
Soil Description	: Red/ brown silt
Other Comments	: Numerous small roots protruding from soil root ball Sweet Chestnut 8 m up wind

TREE SURVEY SHEETS FROM THE SOUTH OF ENGLAND
25th January 1990

Tree Number	: 6
Site	: Killerton
Species	: Lucombe Oak (*Quercus hispanica*)
Location - Street/Park/Hedgerow	: Park
Height (m)	: 20
Crown Spread (m)	: 18
Height to Crown (m)	: 4
Trunk Diameter (Dbh) (cm)	: 140
Disease/Decay	: None
Physical Damage to Roots	: None
Root-Plate:-	
Maximum Depth of Roots (m)	: 1.5
Depth Containing Major Laterals (cm)	: 90
Depth of Soil Above Roots (cm)	: 20
Horizontal Root Plate Diameter (m)	: 4
Horizontal Roots Protruding (m)	: 2 m - 3 long roots
Vertical Root Plate Radius (m)	: 2.5
Vertical Roots Protruding (m)	: 1
Thickness of Roots at Snapping Point (mm)	: 4, 5, 15, 15, 60 x 44, 53 x 62, 60 x 80
Soil Description	: Brick red firm silty clay 50cm top soil (deep) vertical fissures exploited by rootlets
Other Comments	: Many thin flat roots, 13 x 6 mm at base of root plate

TREE SURVEY SHEETS FROM THE SOUTH OF ENGLAND
25th January 1990

Tree Number	: 7
Site	: Killerton
Species	: English Oak (*Quercus robur*)
Location - Street/Park/Hedgerow	: Park
Height (m)	: 22
Crown Spread (m)	: 20
Height to Crown (m)	: 7
Trunk Diameter (Dbh) (cm)	: 130-140
Disease/Decay	: Windward roots rotten
Physical Damage to Roots	: Very little live roots
Root-Plate:-	
Maximum Depth of Roots (m)	: 1
Depth Containing Major Laterals (cm)	: 50
Depth of Soil Above Roots (cm)	: -
Horizontal Root Plate Diameter (m)	: 5
Horizontal Roots Protruding (m)	: -
Vertical Root Plate Radius (m)	: 2
Vertical Roots Protruding (m)	: -
Thickness of Roots at Snapping Point (mm)	:
Soil Description	: Red/ brown clayey silt
Other Comments	: Very few young roots

TREE SURVEY SHEETS FROM THE SOUTH OF ENGLAND
25th January 1990

Tree Number	: 8
Site	: Killerton
Species	: English Oak (*Quercus robur*)
Location - Street/Park/Hedgerow	: Park
Height (m)	: 16
Crown Spread (m)	: 11
Height to Crown (m)	: 4
Trunk Diameter (Dbh) (cm)	: 40
Disease/Decay	: None
Physical Damage to Roots	: None
Root-Plate:-	
Maximum Depth of Roots (m)	: 130
Depth Containing Major Laterals (cm)	: -
Depth of Soil Above Roots (cm)	: 8
Horizontal Root Plate Diameter (m)	: 3
Horizontal Roots Protruding (m)	: 2
Vertical Root Plate Radius (m)	: 2
Vertical Roots Protruding (m)	: 1
Thickness of Roots at Snapping Point (mm)	: 2, 3, 4, 4, 5, 5, 6, 6, 7, 12, 30,
Soil Description	: Red/ brown firm clayey silt
Other Comments	:

TREE SURVEY SHEETS FROM THE SOUTH OF ENGLAND
25th January 1990

Tree Number	: 9
Site	: Killerton
Species	: English Oak (*Quercus robur*)
Location - Street/Park/Hedgerow	: Park
Height (m)	: 17
Crown Spread (m)	: 9 asymmetric, more branches up wind
Height to Crown (m)	: 2
Trunk Diameter (Dbh) (cm)	: 60
Disease/Decay	:
Physical Damage to Roots	:
Root-Plate:-	
Maximum Depth of Roots (m)	:
Depth Containing Major Laterals (cm)	:
Depth of Soil Above Roots (cm)	:
Horizontal Root Plate Diameter (m)	:
Horizontal Roots Protruding (m)	:
Vertical Root Plate Radius (m)	:
Vertical Roots Protruding (m)	:
Thickness of Roots at Snapping Point (mm)	:
Soil Description	:
Other Comments	: Standing

TREE SURVEY SHEETS FROM THE SOUTH OF ENGLAND
25th January 1990

Tree Number	: 10
Site	: Killerton
Species	: English Oak (*Quercus robur*)
Location - Street/Park/Hedgerow	: Park
Height (m)	: 26
Crown Spread (m)	: 24
Height to Crown (m)	: 5
Trunk Diameter (Dbh) (cm)	: 160
Disease/Decay	:
Physical Damage to Roots	:
Root-Plate:-	
Maximum Depth of Roots (m)	:
Depth Containing Major Laterals (cm)	:
Depth of Soil Above Roots (cm)	:
Horizontal Root Plate Diameter (m)	:
Horizontal Roots Protruding (m)	:
Vertical Root Plate Radius (m)	:
Vertical Roots Protruding (m)	:
Thickness of Roots at Snapping Point (mm)	:
Soil Description	:
Other Comments	: Standing

TREE SURVEY SHEETS FROM THE SOUTH OF ENGLAND
25th January 1990

Tree Number	: 11
Site	: Killerton
Species	: Beech (*Fagus sylvatica*)
Location - Street/Park/Hedgerow	: Park
Height (m)	: 23
Crown Spread (m)	: 9 asymmetric
Height to Crown (m)	: 6
Trunk Diameter (Dbh) (cm)	: 55
Disease/Decay	: None
Physical Damage to Roots	: None
Root-Plate:-	
Maximum Depth of Roots (m)	: 130
Depth Containing Major Laterals (cm)	: -
Depth of Soil Above Roots (cm)	: 10
Horizontal Root Plate Diameter (m)	: 3
Horizontal Roots Protruding (m)	: 1
Vertical Root Plate Radius (m)	: 2
Vertical Roots Protruding (m)	: 0.5
Thickness of Roots at Snapping Point (mm)	: 4, 5, 7, 8, 10, 15, 20, fibrous, no major roots broken, 8 x 40, 12 x 4, 6 x 4 - vertical roots flattened
Soil Description	: Red/brown silt - drier
Other Comments	: 1 of a group of 8 trees, only one that fell. Slight gap on windward side to let wind into the tree

TREE SURVEY SHEETS FROM THE SOUTH OF ENGLAND

25th January 1990

Tree Number	: 12
Site	: Killerton
Species	: Beech (*Fagus sylvatica*)
Location - Street/Park/Hedgerow	: Park
Height (m)	: 21
Crown Spread (m)	: 13 asymmetric
Height to Crown (m)	: 7
Trunk Diameter (Dbh) (cm)	: 65
Disease/Decay	:
Physical Damage to Roots	:
Root-Plate:-	
Maximum Depth of Roots (m)	:
Depth Containing Major Laterals (cm)	:
Depth of Soil Above Roots (cm)	:
Horizontal Root Plate Diameter (m)	:
Horizontal Roots Protruding (m)	:
Vertical Root Plate Radius (m)	:
Vertical Roots Protruding (m)	:
Thickness of Roots at Snapping Point (mm)	:
Soil Description	:
Other Comments	: Standing in same group as number 11

TREE SURVEY SHEETS FROM THE SOUTH OF ENGLAND
25th January 1990

Tree Number	: 13
Site	: Killerton
Species	: English Oak (*Quercus robur*)
Location - Street/Park/Hedgerow	: Park/Hedgerow
Height (m)	: 20
Crown Spread (m)	: 16
Height to Crown (m)	: 3
Trunk Diameter (Dbh) (cm)	: 170
Disease/Decay	: Roots in heart of tree-dead windward
Physical Damage to Roots	: Windward roots restricted by road
Root-Plate:-	
Maximum Depth of Roots (m)	: (Roots growing down the
Depth Containing Major Laterals (cm)	: sloping sides of a bank).
Depth of Soil Above Roots (cm)	:
Horizontal Root Plate Diameter (m)	
Horizontal Roots Protruding (m)	: -
Vertical Root Plate Radius (m)	: 2
Vertical Roots Protruding (m)	: -
Thickness of Roots at Snapping Point (mm)	:
Soil Description	:
Other Comments	: Peripheral soil cracks 3 m from centre of root plates

TREE SURVEY SHEETS FROM THE SOUTH OF ENGLAND
25th January 1990

Tree Number	: 14
Site	: Killerton
Species	: Beech (*Fagus sylvatica*)
Location - Street/Park/Hedgerow	: Park
Height (m)	: 12
Crown Spread (m)	: 6
Height to Crown (m)	: 3
Trunk Diameter (Dbh) (cm)	: 32
Disease/Decay	: None
Physical Damage to Roots	: None
Root-Plate:-	
Maximum Depth of Roots (m)	: 12
Depth Containing Major Laterals (cm)	: -
Depth of Soil Above Roots (cm)	: -
Horizontal Root Plate Diameter (m)	: 2.5
Horizontal Roots Protruding (m)	: -
Vertical Root Plate Radius (m)	: 1.5
Vertical Roots Protruding (m)	: None
Thickness of Roots at Snapping Point (mm)	: 2, 3, 5, 6, 11, 18
Soil Description	: Red/ brown sandy silt
Other Comments	:

TREE SURVEY SHEETS FROM THE SOUTH OF ENGLAND
25th January 1990

Tree Number	: 15
Site	: Killerton
Species	: English Oak (*Quercus robur*)
Location - Street/Park/Hedgerow	: Park
Height (m)	: 11
Crown Spread (m)	: 5
Height to Crown (m)	: 5
Trunk Diameter (Dbh) (cm)	: 31
Disease/Decay	: None
Physical Damage to Roots	: None
Root-Plate:-	
Maximum Depth of Roots (m)	: 1.5+
Depth Containing Major Laterals (cm)	: -
Depth of Soil Above Roots (cm)	: -
Horizontal Root Plate Diameter (m)	: 1.5
Horizontal Roots Protruding (m)	: 1 and 1.5
Vertical Root Plate Radius (m)	: 0.75
Vertical Roots Protruding (m)	: 1
Thickness of Roots at Snapping Point (mm)	: 7, 8, 13, 15, 16, 17, 20
Soil Description	: Red/ brown sandy silt
Other Comments	: Droppers, 20 mm, 35 mm, 8 mm, twisted together and growing down as if it were a 'tap root'

TREE SURVEY SHEETS FROM THE SOUTH OF ENGLAND
25th January 1990

Tree Number	: 16
Site	: Killerton
Species	: English Oak (*Quercus robur*)
Location - Street/Park/Hedgerow	: Park
Height (m)	: 10
Crown Spread (m)	: 4
Height to Crown (m)	: 3
Trunk Diameter (Dbh) (cm)	: 22
Disease/Decay	: None
Physical Damage to Roots	: None
Root-Plate:-	
Maximum Depth of Roots (m)	:
Depth Containing Major Laterals (cm)	:
Depth of Soil Above Roots (cm)	:
Horizontal Root Plate Diameter (m)	:
Horizontal Roots Protruding (m)	:
Vertical Root Plate Radius (m)	:
Vertical Roots Protruding (m)	:
Thickness of Roots at Snapping Point (mm)	:
Soil Description	:
Other Comments	: Tree leaning at angle, surrounding ground raised. 6 cm cracks in ground 60 x 80 cm from base of tree

TREE SURVEY SHEETS FROM THE SOUTH OF ENGLAND
25th January 1990

Tree Number	: 17
Site	: Killerton
Species	: English Oak (*Quercus robur*)
Location - Street/Park/Hedgerow	: Park
Height (m)	: 10
Crown Spread (m)	: 3
Height to Crown (m)	: 2
Trunk Diameter (Dbh) (cm)	: 23
Disease/Decay	:
Physical Damage to Roots	:
Root-Plate:-	
Maximum Depth of Roots (m)	:
Depth Containing Major Laterals (cm)	:
Depth of Soil Above Roots (cm)	:
Horizontal Root Plate Diameter (m)	:
Horizontal Roots Protruding (m)	:
Vertical Root Plate Radius (m)	:
Vertical Roots Protruding (m)	:
Thickness of Roots at Snapping Point (mm)	:
Soil Description	:
Other Comments	: Standing but leaning at a slight angle - may have grown that way

TREE SURVEY SHEETS FROM THE SOUTH OF ENGLAND
25th January 1990

Tree Number	: 18
Site	: Killerton
Species	: English Oak (*Quercus robur*)
Location - Street/Park/Hedgerow	: Park
Height (m)	: Large
Crown Spread (m)	: -
Height to Crown (m)	: -
Trunk Diameter (Dbh) (cm)	: -
Disease/Decay	: Roots on leeside rotten
Physical Damage to Roots	:
Root-Plate:-	
Maximum Depth of Roots (m)	:
Depth Containing Major Laterals (cm)	:
Depth of Soil Above Roots (cm)	:
Horizontal Root Plate Diameter (m)	:
Horizontal Roots Protruding (m)	:
Vertical Root Plate Radius (m)	:
Vertical Roots Protruding (m)	:
Thickness of Roots at Snapping Point (mm)	:
Soil Description	:
Other Comments	: Ground heave raised by good roots

TREE SURVEY SHEETS FROM THE SOUTH OF ENGLAND
25th January 1990

Tree Number	: 19
Site	: Killerton
Species	: English Oak (*Quercus robur*)
Location - Street/Park/Hedgerow	: Park
Height (m)	: 20-25 (top missing)
Crown Spread (m)	: -
Height to Crown (m)	: 4
Trunk Diameter (Dbh) (cm)	: 86
Disease/Decay	:
Physical Damage to Roots	:
Root-Plate:-	
Maximum Depth of Roots (m)	:
Depth Containing Major Laterals (cm)	:
Depth of Soil Above Roots (cm)	:
Horizontal Root Plate Diameter (m)	:
Horizontal Roots Protruding (m)	:
Vertical Root Plate Radius (m)	:
Vertical Roots Protruding (m)	:
Thickness of Roots at Snapping Point (mm)	:
Soil Description	:
Other Comments	: Leaning - but pushed by other Oaks

TREE SURVEY SHEETS FROM THE SOUTH OF ENGLAND
25th January 1990

Tree Number	: 20
Site	: Llanhydroch
Species	: Beech (*Fagus sylvatica*)
Location - Street/Park/Hedgerow	: Park
Height (m)	: 18
Crown Spread (m)	: 18
Height to Crown (m)	: 4
Trunk Diameter (Dbh) (cm)	: 100
Disease/Decay	: None
Physical Damage to Roots	: None
Root-Plate:-	
Maximum Depth of Roots (m)	: 1.1
Depth Containing Major Laterals (cm)	: -
Depth of Soil Above Roots (cm)	: 12
Horizontal Root Plate Diameter (m)	: 5
Horizontal Roots Protruding (m)	: 1
Vertical Root Plate Radius (m)	: 3
Vertical Roots Protruding (m)	: 1
Thickness of Roots at Snapping Point (mm)	: 4, 10, 12, 13, 21, 24, 33
Soil Description	: Yellow/ brown highly weathered shale Very gravelly clay
Other Comments	:

TREE SURVEY SHEETS FROM THE SOUTH OF ENGLAND
25th January 1990

Tree Number	: 21
Site	: Llanhydroch
Species	: English Oak (*Quercus robur*)
Location - Street/Park/Hedgerow	: Park
Height (m)	: 20
Crown Spread (m)	: 5
Height to Crown (m)	: 9
Trunk Diameter (Dbh) (cm)	: 80
Disease/Decay	: None
Physical Damage to Roots	: None
Root-Plate:-	
Maximum Depth of Roots (m)	: -
Depth Containing Major Laterals (cm)	: -
Depth of Soil Above Roots (cm)	: -
Horizontal Root Plate Diameter (m)	: 3.5
Horizontal Roots Protruding (m)	: -
Vertical Root Plate Radius (m)	: -
Vertical Roots Protruding (m)	: -
Thickness of Roots at Snapping Point (mm)	: 7, 10, 30, 35 - few roots
Soil Description	: Clay with angular stone
Other Comments	: Tree leaning

TREE SURVEY SHEETS FROM THE SOUTH OF ENGLAND
25th January 1990

Tree Number	: 22
Site	: Llanhydroch
Species	: Beech (*Fagus sylvatica*)
Location - Street/Park/Hedgerow	: Park
Height (m)	: 18
Crown Spread (m)	: 12
Height to Crown (m)	: 3, twin forked
Trunk Diameter (Dbh) (cm)	: 100
Disease/Decay	: None
Physical Damage to Roots	: None
Root-Plate:-	
Maximum Depth of Roots (m)	: 1.5
Depth Containing Major Laterals (cm)	: 100
Depth of Soil Above Roots (cm)	: 20
Horizontal Root Plate Diameter (m)	: 5
Horizontal Roots Protruding (m)	: 0.6
Vertical Root Plate Radius (m)	: 3
Vertical Roots Protruding (m)	: 0.5
Thickness of Roots at Snapping Point (mm)	: 3, 6, 8, 12, 13, 23, 24, 39 few roots protruding micro rootlets at base
Soil Description	: Clay with slaty stones angularly layered
Other Comments	: On windward edge of group of 9 Beech, 2 fallen

TREE SURVEY SHEETS FROM THE SOUTH OF ENGLAND
25th January 1990

Tree Number	: 23
Site	: Llanhydroch
Species	: Beech (*Fagus sylvatica*)
Location - Street/Park/Hedgerow	: Park
Height (m)	: 19
Crown Spread (m)	: 8
Height to Crown (m)	: 6
Trunk Diameter (Dbh) (cm)	: 75
Disease/Decay	: None
Physical Damage to Roots	: None
Root-Plate:-	
Maximum Depth of Roots (m)	: 1.3
Depth Containing Major Laterals (cm)	: 100
Depth of Soil Above Roots (cm)	: 10
Horizontal Root Plate Diameter (m)	: 4
Horizontal Roots Protruding (m)	: 0.5
Vertical Root Plate Radius (m)	: 2.5
Vertical Roots Protruding (m)	: 0.3-0.5
Thickness of Roots at Snapping Point (mm)	: 15, 16, 24, 29, 30 - stocky but few rootlets from base- 3, 4, 6
Soil Description	: Clayey with slaty flints
Other Comments	: On windward side of group of 9 Beech 2 fallen

TREE SURVEY SHEETS FROM THE SOUTH OF ENGLAND
25th January 1990

Tree Number	: 24
Site	: Llanhydroch
Species	: Beech (*Fagus sylvatica*)
Location - Street/Park/Hedgerow	: Park
Height (m)	: 21
Crown Spread (m)	: 7
Height to Crown (m)	: 5
Trunk Diameter (Dbh) (cm)	: 110
Disease/Decay	:
Physical Damage to Roots	:
Root-Plate:-	
Maximum Depth of Roots (m)	:
Depth Containing Major Laterals (cm)	:
Depth of Soil Above Roots (cm)	:
Horizontal Root Plate Diameter (m)	:
Horizontal Roots Protruding (m)	:
Vertical Root Plate Radius (m)	:
Vertical Roots Protruding (m)	:
Thickness of Roots at Snapping Point (mm)	:
Soil Description	:
Other Comments	: Standing in middle of group of 9 Beech

TREE SURVEY SHEETS FROM THE SOUTH OF ENGLAND
25th January 1990

Tree Number	: 25
Site	: Llanhydroch
Species	: Beech (*Fagus sylvatica*)
Location - Street/Park/Hedgerow	: Park
Height (m)	: 26
Crown Spread (m)	: 9
Height to Crown (m)	: 4
Trunk Diameter (Dbh) (cm)	: 100
Disease/Decay	: None
Physical Damage to Roots	: None
Root-Plate:-	
Maximum Depth of Roots (m)	: 1.2
Depth Containing Major Laterals (cm)	: 90
Depth of Soil Above Roots (cm)	: 15
Horizontal Root Plate Diameter (m)	: 5.5
Horizontal Roots Protruding (m)	: 1 (1 root)
Vertical Root Plate Radius (m)	: 2.5
Vertical Roots Protruding (m)	: 0.5 very few (6)
Thickness of Roots at Snapping Point (mm)	: -
Soil Description	: Clayey soil - less shale than nos. 21-23
Other Comments	:

TREE SURVEY SHEETS FROM THE SOUTH OF ENGLAND
25th January 1990

Tree Number	: 23
Site	: Llanhydroch
Species	: Beech (*Fagus sylvatica*)
Location - Street/Park/Hedgerow	: Park
Height (m)	: 25
Crown Spread (m)	: 15
Height to Crown (m)	: 6
Trunk Diameter (Dbh) (cm)	: 130
Disease/Decay	: None
Physical Damage to Roots	: None
Root-Plate:-	
Maximum Depth of Roots (m)	: 50
Depth Containing Major Laterals (cm)	: -
Depth of Soil Above Roots (cm)	: 0
Horizontal Root Plate Diameter (m)	: 5
Horizontal Roots Protruding (m)	: 1
Vertical Root Plate Radius (m)	: 2.5
Vertical Roots Protruding (m)	: 0.5
Thickness of Roots at Snapping Point (mm)	: 4, 5, 16, 22, 35 very few
Soil Description	: Green/brown slightly organic very silty Clay with gravel sized shale fragments
Other Comments	:

TREE SURVEY SHEETS FROM THE SOUTH OF ENGLAND
25th January 1990

Tree Number	: 27
Site	: Saltram House
Species	: Lucombe Oak (*Quercus hisparica*)
Location - Street/Park/Hedgerow	: Park
Height (m)	: 18
Crown Spread (m)	: 20
Height to Crown (m)	: 4
Trunk Diameter (Dbh) (cm)	: 95
Disease/Decay	: None
Physical Damage to Roots	: None
Root-Plate:-	
Maximum Depth of Roots (m)	: 2
Depth Containing Major Laterals (cm)	: 30
Depth of Soil Above Roots (cm)	: 10
Horizontal Root Plate Diameter (m)	: 4
Horizontal Roots Protruding (m)	: 1, 0.5 - 3 roots
Vertical Root Plate Radius (m)	: 1.5
Vertical Roots Protruding (m)	: 0
Thickness of Roots at Snapping Point (mm)	: 3, 5, 6, 8, - droppers 42, 58 - laterals torn - not clean snaps
Soil Description	: Brown/grey highly fissile weak shale with a trace of brown clay on surfaces
Other Comments	: Vertical roots in centre of trunk, follow grain of rock - very slaty Vertical roots flattened

TREE SURVEY SHEETS FROM THE SOUTH OF ENGLAND
25th January 1990

Tree Number	: 28
Site	: Saltram House
Species	: Norway Maple (*Acer platanoides*)
Location - Street/Park/Hedgerow	: Park
Height (m)	: 13
Crown Spread (m)	: 14
Height to Crown (m)	: 3
Trunk Diameter (Dbh) (cm)	: 55
Disease/Decay	: None
Physical Damage to Roots	: Stream flowing very close/ below roots
Root-Plate:-	
Maximum Depth of Roots (m)	: 1.5
Depth Containing Major Laterals (cm)	: 0.5-0.8
Depth of Soil Above Roots (cm)	: -
Horizontal Root Plate Diameter (m)	: 3
Horizontal Roots Protruding (m)	: 0.5
Vertical Root Plate Radius (m)	: 2
Vertical Roots Protruding (m)	: 0
Thickness of Roots at Snapping Point (mm)	: 1, 2, 2, 3, 3, 4, 8, 15 lots of little roots
Soil Description	: Dark grey/brown friable organic clayey silt with shale fragments (loam in agricultural terms)
Other Comments	:

TREE SURVEY SHEETS FROM THE SOUTH OF ENGLAND
25th January 1990

Tree Number	: 29
Site	: Saltram House
Species	: Lime (*Tilia*)
Location - Street/Park/Hedgerow	: Park
Height (m)	: 19
Crown Spread (m)	: 18
Height to Crown (m)	: 4
Trunk Diameter (Dbh) (cm)	: 85
Disease/Decay	: None
Physical Damage to Roots	: None
Root-Plate:-	
Maximum Depth of Roots (m)	: 1.75
Depth Containing Major Laterals (cm)	: 40
Depth of Soil Above Roots (cm)	: 10
Horizontal Root Plate Diameter (m)	: 5
Horizontal Roots Protruding (m)	: 0.5 (2 roots)
Vertical Root Plate Radius (m)	: 2.5
Vertical Roots Protruding (m)	: 0.3 very few
Thickness of Roots at Snapping Point (mm)	: -
Soil Description	: Blue/ grey highly fissile weak shale with a little orangey brown clay on surfaces
Other Comments	: Roots growing down fissures - flattened

TREE SURVEY SHEETS FROM THE SOUTH OF ENGLAND
25th January 1990

Tree Number	: 30
Site	: Saltram House
Species	: Lime (*Tilia*)
Location - Street/Park/Hedgerow	: Park
Height (m)	: 15
Crown Spread (m)	: 22
Height to Crown (m)	: 5
Trunk Diameter (Dbh) (cm)	: 90
Disease/Decay	: None
Physical Damage to Roots	: None
Root-Plate:-	
Maximum Depth of Roots (m)	: 1
Depth Containing Major Laterals (cm)	: 60-70
Depth of Soil Above Roots (cm)	: 10
Horizontal Root Plate Diameter (m)	: 5
Horizontal Roots Protruding (m)	: 1
Vertical Root Plate Radius (m)	: 2.5
Vertical Roots Protruding (m)	: 1
Thickness of Roots at Snapping Point (mm)	: 80, 100, 140, 150 - radial laterals Very large and strong
Soil Description	: Slaty and big slaty stones
Other Comments	:

TREE SURVEY SHEETS FROM THE SOUTH OF ENGLAND
25th January 1990

Tree Number	: 31
Site	: Saltram House
Species	: Pine (*Pinus*)
Location - Street/Park/Hedgerow	: Park/ Woodland Boundary
Height (m)	: 15
Crown Spread (m)	: 9
Height to Crown (m)	: 4
Trunk Diameter (Dbh) (cm)	: 65
Disease/Decay	: None
Physical Damage to Roots	: None
Root-Plate:-	
Maximum Depth of Roots (m)	: 1.3
Depth Containing Major Laterals (cm)	: 30
Depth of Soil Above Roots (cm)	: 3
Horizontal Root Plate Diameter (m)	: 3.5
Horizontal Roots Protruding (m)	: 1, 0.5
Vertical Root Plate Radius (m)	: 2.3
Vertical Roots Protruding (m)	: 2 (few)
Thickness of Roots at Snapping Point (mm)	: 80, 80, 90, 120 - laterals, 5, 6 -droppers
Soil Description	:
Other Comments	: Growing on brow of hill

TREE SURVEY SHEETS FROM THE SOUTH OF ENGLAND
25th January 1990

Tree Number	: 32
Site	: Saltram House
Species	: Lime (*Tilia*)
Location - Street/Park/Hedgerow	: Park
Height (m)	: 14
Crown Spread (m)	: 13
Height to Crown (m)	: 2
Trunk Diameter (Dbh) (cm)	: 70
Disease/Decay	: None
Physical Damage to Roots	: None
Root-Plate:-	
Maximum Depth of Roots (m)	: -
Depth Containing Major Laterals (cm)	: 25
Depth of Soil Above Roots (cm)	: 8
Horizontal Root Plate Diameter (m)	: 4.5
Horizontal Roots Protruding (m)	: 1.5, 2
Vertical Root Plate Radius (m)	: 2.4
Vertical Roots Protruding (m)	: 0.5 few
Thickness of Roots at Snapping Point (mm)	: 1, 2, 8, 15, 35, 47
Soil Description	: Very slaty soil
Other Comments	: Central roots very flattened Many fibrous roots

TREE SURVEY SHEETS FROM THE SOUTH OF ENGLAND
25th January 1990

Tree Number : 33

Site : Saltram House

Species : Sycamore (*Acer pseudoplatanus*)

Location - Street/Park/Hedgerow : Park

Height (m) :
Crown Spread (m) :
Height to Crown (m) :
Trunk Diameter (Dbh) (cm) :

Disease/Decay : Dead

Physical Damage to Roots :

Root-Plate:-

Maximum Depth of Roots (m) :
Depth Containing Major Laterals (cm) :
Depth of Soil Above Roots (cm) :
Horizontal Root Plate Diameter (m) :
Horizontal Roots Protruding (m) :
Vertical Root Plate Radius (m) :
Vertical Roots Protruding (m) :
Thickness of Roots at Snapping Point (mm) :

Soil Description :

Other Comments :

TREE SURVEY SHEETS FROM THE SOUTH OF ENGLAND
25th January 1990

Tree Number	: 34
Site	: Saltram House
Species	: Lime (*Tilia*)
Location - Street/Park/Hedgerow	: Park
Height (m)	: 33
Crown Spread (m)	: 14
Height to Crown (m)	: 2 - triple fork
Trunk Diameter (Dbh) (cm)	: 150, 75
Disease/Decay	: None
Physical Damage to Roots	: None
Root-Plate:-	
Maximum Depth of Roots (m)	: -
Depth Containing Major Laterals (cm)	: 40
Depth of Soil Above Roots (cm)	: 4
Horizontal Root Plate Diameter (m)	: 3.5
Horizontal Roots Protruding (m)	: 1, 1
Vertical Root Plate Radius (m)	: 2.5
Vertical Roots Protruding (m)	: 0.75 - 4 roots
Thickness of Roots at Snapping Point (mm)	:
Soil Description	:
Other Comments	: Peripheral droppers 3 m + 2 m Snapped at 90 mm diameter 1 of group of 3 Limes - 2 fell, the other fallen, one had extensive root rot

TREE SURVEY SHEETS FROM THE SOUTH OF ENGLAND
25th January 1990

Tree Number	: 35
Site	: Saltram House
Species	: Lime (*Tilia*)
Location - Street/Park/Hedgerow	: Park
Height (m)	: 25
Crown Spread (m)	: 10
Height to Crown (m)	: 9
Trunk Diameter (Dbh) (cm)	: 75
Disease/Decay	: None
Physical Damage to Roots	: None
Root-Plate:-	
Maximum Depth of Roots (m)	:
Depth Containing Major Laterals (cm)	:
Depth of Soil Above Roots (cm)	:
Horizontal Root Plate Diameter (m)	:
Horizontal Roots Protruding (m)	:
Vertical Root Plate Radius (m)	:
Vertical Roots Protruding (m)	:
Thickness of Roots at Snapping Point (mm)	:
Soil Description	:
Other Comments	: Standing. Group of 3, other 2 fell

Appendix C

Calibrations

Wind Anemometer, Linear Potentiometers and Linear Transducers

Anemometer Calibration

The triaxial wind anemometer was calibrated in the wind tunnel using a mercury filled pitot static tube. Wind velocity was calculated from the increased height of the mercury column.

$$\text{Pressure } mm_{water} = \frac{v^2}{2g}$$

where ρ_w = density of water

ρ_a = density of air

$$\text{for Air } mm = \frac{v^2}{2g} \times \frac{\rho_w}{\rho_a} = \frac{v^2}{2g} \times \frac{1000}{1.225}$$

v = wind velocity

g = acceleration due to gravity

lets call the mercury height H, measured in mm

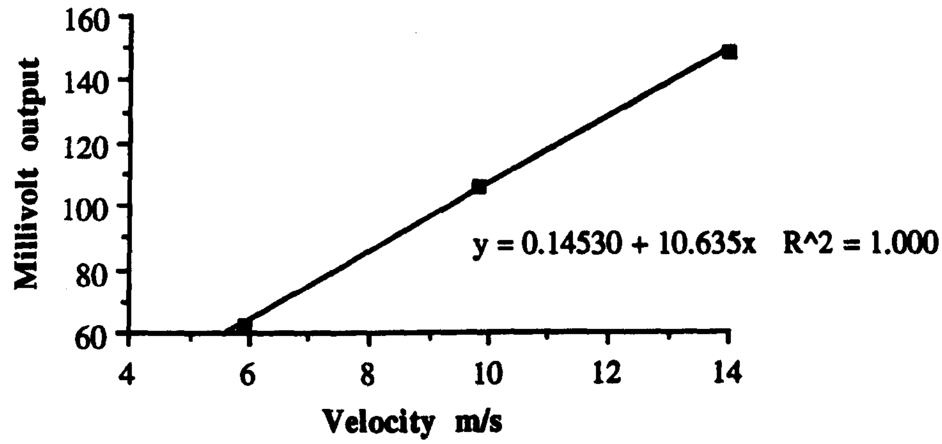
$$= \frac{v^2}{2g} \text{ water}$$

$$\frac{v^2}{2g} \text{ air} = H \times \frac{1000}{1.225} \times \frac{1}{1000}$$

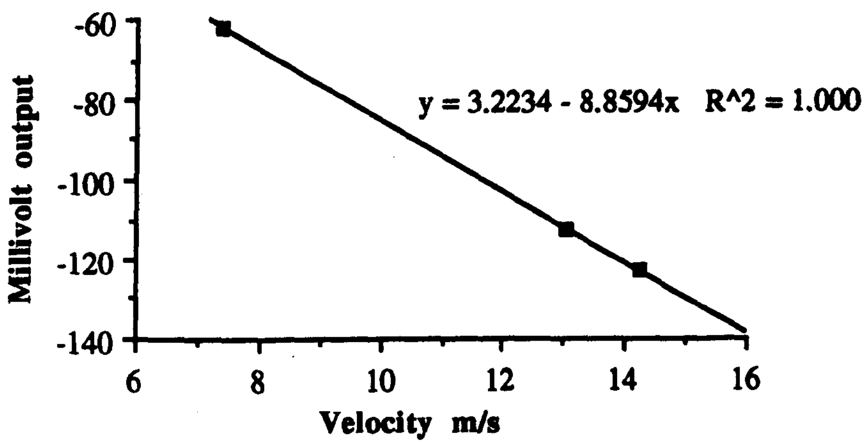
$$v = \sqrt{\frac{2Hg}{1.225}} = \sqrt{\frac{19.62}{1.225}} H$$

H reading (mm)	Corrected H	X reading (mV)	Y reading (mV)	W reading (mV)	Output reading V	Velocity (m/s)
2.11						
4.28	2.17	45	**625**		Y 1.245	**5.895**
8.16	6.05	75	**1055**	35	Y 2.100	**9.844**
14.32	12.21	100	**1485**	49	Y 3.000	**13.980**
5.51	3.40	**-621**	-41	-65	X 1.240	**7.379**
12.71	10.60	**-1125**	-65	-110	X 2.251	**13.030**
14.77	12.66	**-1227**	-75	-102	X 2.450	**14.240**
4.30	2.19	-26	82	**-642**	W 1.240	**5.922**
7.93	5.82	-55	145	**-1055**	W 2.060	**9.655**
14.31	12.20	-70	210	**-1475**	W 3.020	**13.980**

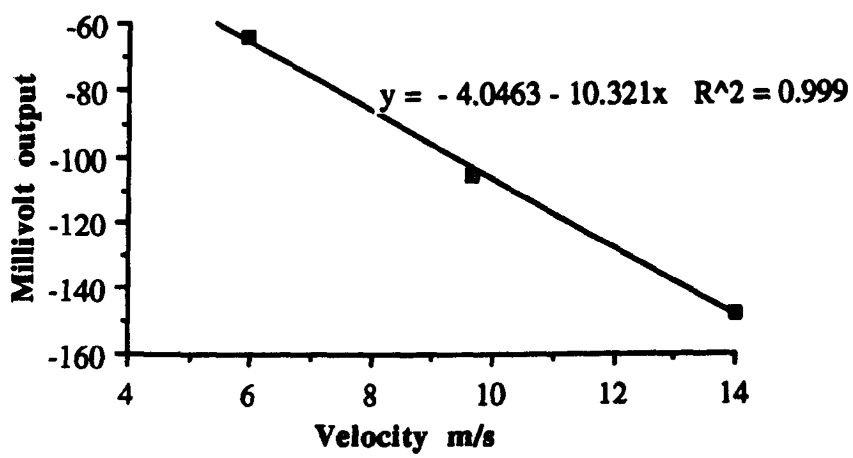
The above table collates all the data collected during calibration. Velocity was calculated from the above formula. Bold numbers are plotted on graphs a-c and regression lines calculated so a calibration factor is given for each anemometer head.
The output reading is taken before the signal enters the datalogger.
For the datalogger readings taken on 18th Jan 1990 and 22nd Feb 1990, the mVolt output has been multiplied by a factor of 10! This is accounted for by changing the calibration by *10 but windspeeds > 7ms^{-1} exceed 6999mV and therefore go off the datalogger scale.



a) Anemometer calibration in the wind direction



b) Anemometer calibration across the wind direction



c) Anemometer calibration in vertical direction

Figure C1 Anemometer Calibration

Calibration values of Linear Potentiometers and Linear Transducers

The following values for the linear potentiometers correspond to the multiplication factor required to convert the voltage output from the datalogger to displacement measured in millimetres.

Linear potentiometer 1	9.8257
Linear potentiometer 2	9.8277
Linear potentiometer 3	9.8232
Linear potentiometer 4	9.8011
Linear potentiometer 5	9.7806
Linear potentiometer 6	9.8405

The following values correspond to the sensitivity of the linear transducers. These are the values by which the datalogger output must be divided to gain displacement values measured in millimetres.

Linear transducer no. 48	0.001814
Linear transducer no. 53	0.001837
Linear transducer no. 58	0.002747
Linear transducer no. 59	0.001922

Appendix D

Experimental Layouts

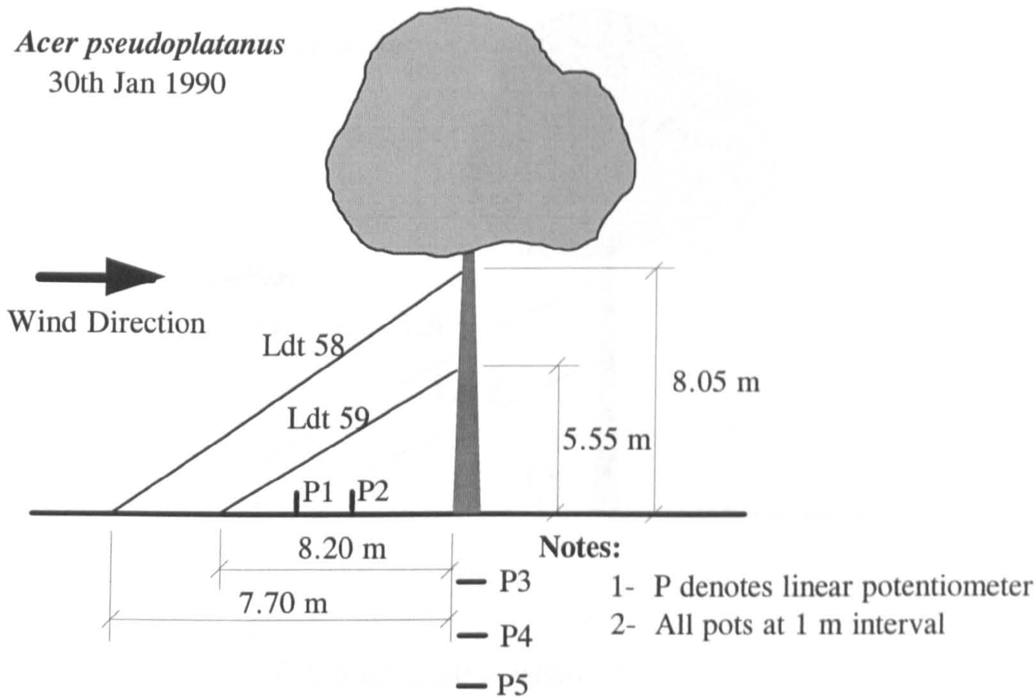
Experiment 1: *Acer pseudoplatanus* - monitored in the wind

Experiment 2: *Fagus sylvatica* - monitored in the wind

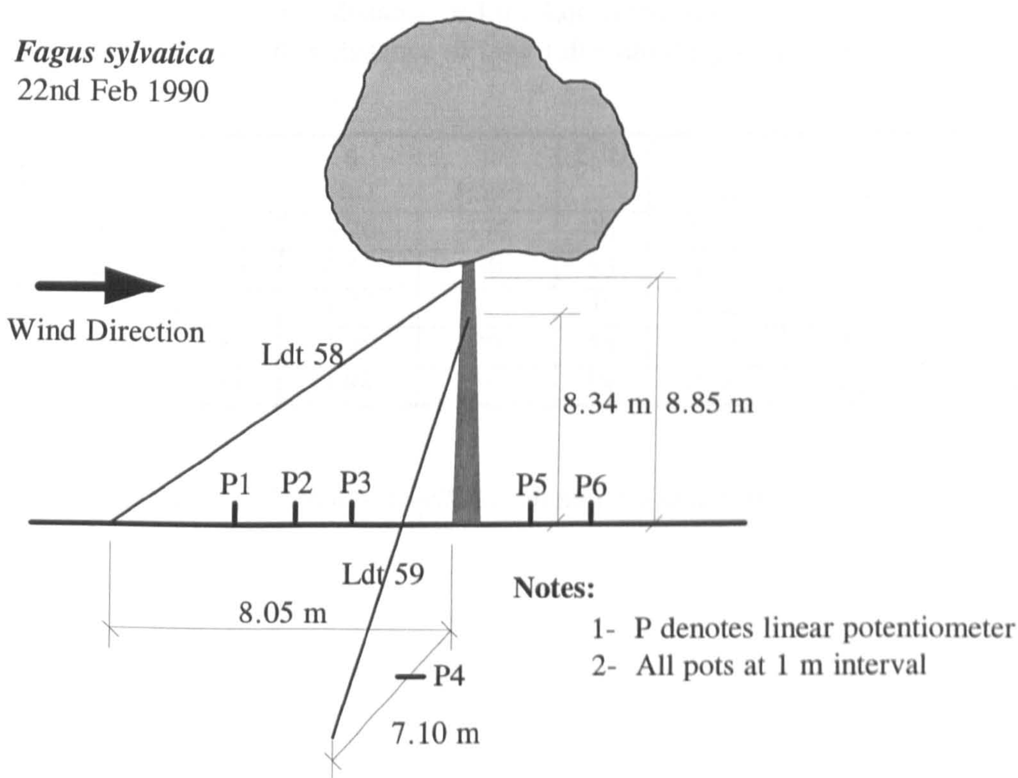
Experiment 3: *Platanus acerifolia* - monitored in the wind

Experiment 4: *Platanus acerifolia* - monitored during enforced tree oscillation

Experiment 5: Blidworth trees - monitored during enforced tree oscillation

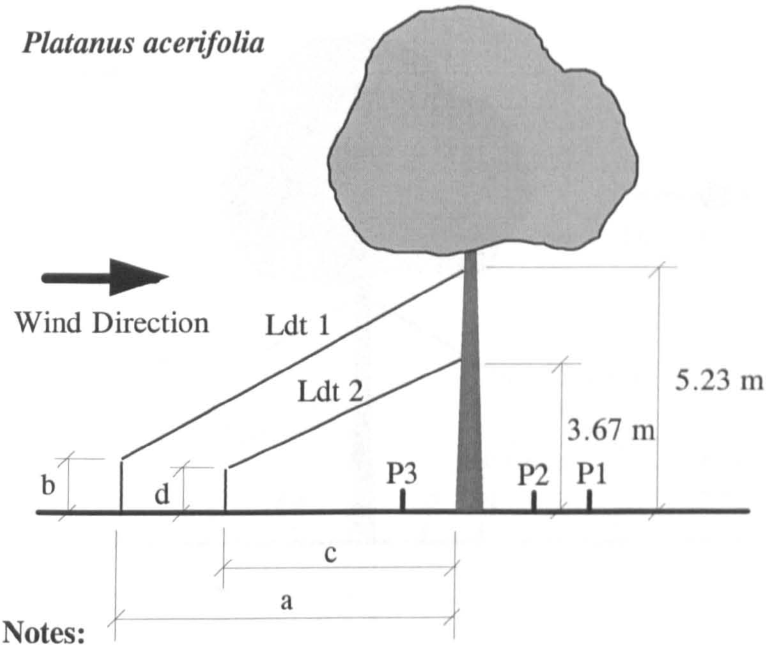


Experiment 1: *Acer pseudoplatanus* - monitored in the wind



Experiment 2: *Fagus sylvatica* - monitored in the wind

Platanus acerifolia



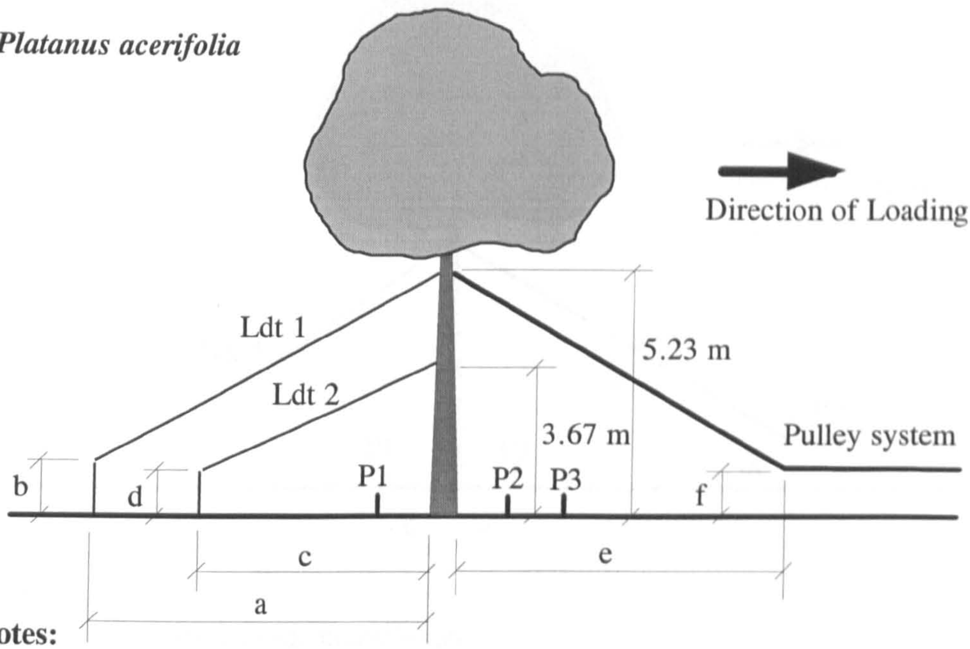
Notes:

1- P denotes linear potentiometer
2- All pots at 0.5 m interval
3- a = distance of High Ldt to tree (m)
4- b = distance of High Ldt from the ground (mm)
5- a = distance of Low Ldt to tree (m)
6- b = distance of Low Ldt from the ground (mm)

Date	a (m)	b (mm)	Ldt1	c (m)	d (mm)	Ldt2
6th Sept 1990	5.20	170	48	5.50	190	59
19th Sept 1990	4.43	70	53	4.73	35	59
5th Jan 1991	4.37	-	59	4.00	-	53
24th Sept 1991	3.59	30	59	4.55	40	53
10th March 1992	3.84	55	59	4.60	20	53

Experiment 3: *Platanus acerifolia* - monitored in the wind

Platanus acerifolia



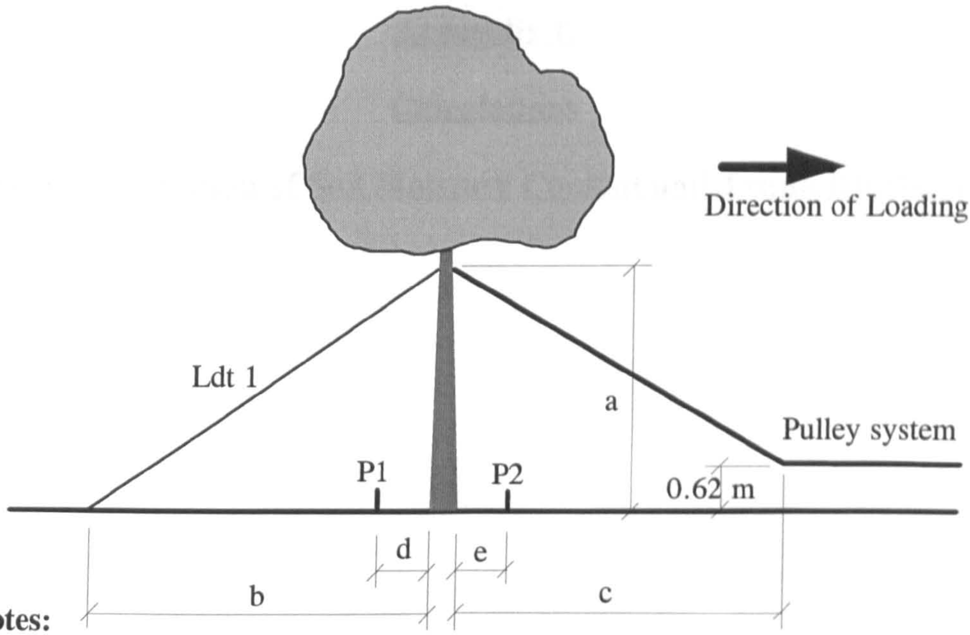
Notes:

1- P denotes linear potentiometer
2- All pots at 0.5 m interval
3- a = distance of High Ldt to tree (m)
4- b = height of High Ldt from the ground (mm)
5- c = distance of Low Ldt to tree (m)
6- d = height of Low Ldt from the ground (mm)
7- e = distance of pulley to tree (m)
8- f = height of pulley from the ground (m)
9- g = distance of Ldt to tree perpendicular to plane of loading (m)
10- h = height of Ldt (g) from the ground (mm)

Date	a (m)	b (mm)	Ldt 1	c (m)	d (mm)	Ldt 2	e (m)	f (m)	g (m)	h (mm)
11th Dec 1990	4.10	50	59	4.55	40	53	10.2	0.62	-	-
25th April 1991	4.23	60	59	4.56	40	53*	9.06	0.62	4.56	50
22nd Aug 1991	3.60	50	59*	4.55	35	53	-	0.62	4.20	60
11th Dec 1991	3.60	110	59*	4.55	25	53	-	0.62	4.55	25
25th April 1991	4.56	20	59*	3.8	60	53	11.4	0.62	4.86	80

Note: * = Ldt set perpendicular to the plane of loading.

Experiment 4: *Platanus acerifolia* - monitored during enforced tree oscillation



Notes:

1- P denotes linear potentiometer
2- a = height of Ldt and loading point on the tree (m)
3- b = distance of Ldt to the tree (m)
4- c = distance of pulley system to the tree (m)
5- d = distance of pot P1 to the tree (mm)
6- e = distance of pot P2 to the tree (mm)
7- for some trees, the direction of the load was reversed with relation to the pots P1 and P2

Tree No.	a (m)	b (m)	c (m)	Loading from P1 or P2 side	d (mm)	e (mm)
3	3.60	6.00	7.97	P1	230	-
4	3.53	5.84	12.30	P1	220	230
6	3.95	5.76	6.93	P1	230	240
7	3.77	4.88	9.81	P1	210	200

Date: May 1991

Tree No.	a (m)	b (m)	c (m)	Loading from P1 or P2 side	d (mm)	e (mm)
1	2.52	6.45	10.88	P1	270	260
2	3.55	5.65	14.70	P1	160	220
3	3.48	6.47	12.08	P2	-	225
4	3.29	6.15	18.44	P2	225	225
5	3.48	6.01	14.50	P1	235	270
6	3.83	4.66	10.90	P1	230	180
7	3.52	5.04	12.50	P1	235	180
9	4.28	5.46	16.73	P2	235	180

Date: May 1992

Experiment 5: Blidworth trees - monitored during enforced tree oscillation

Appendix E

Calculations

Example Calculation of Soil Moisture Content and Trunk Displacement

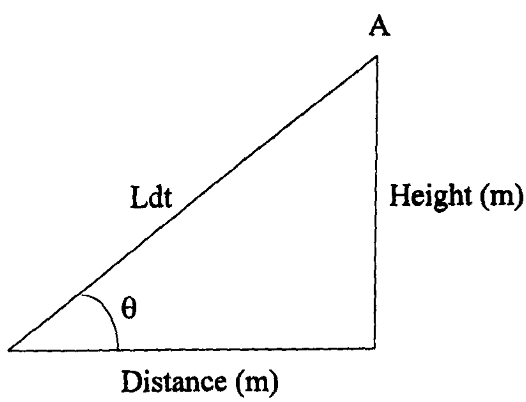
1 Soil Moisture Content Calculation

mass of container and wet soil	= 129.6 g
mass of container and dry soil	= 105.9 g
mass of container when emptied	= 15.7 g

mass of wet soil	= 113.9 g
mass of dry soil	= 90.2 g
mass of water	= 23.7 g

moisture content = (mass of water/ mass of wet soil) . 100
= (23.7/ 113.9) . 100
= 20.8 g_{water}/100 g_{soil}
= 20.8%

2 Trunk Displacement Calculation



Horizontal movement at A

$$\text{Trunk Displacement (mm)} = \frac{\text{Output (mV)}}{1000} \cdot \frac{1}{\text{Ldt sensitivity}} \cdot \frac{1}{\cos\theta}$$