Tree Related Subsidence of Low Rise Buildings and the Management Options

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Member of the Institute of Biology (By Dissertation)

Tree Related Subsidence of Low Rise Buildings and the Management Options

A dissertation presented to the Institute of Biology in fulfilment of the requirements for entry as a Member of the Institute of Biology (MIBiol)

by

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Statement of Originality

I certify that the work reported in this dissertation is my own, unless otherwise referenced and has not been submitted for any degree to any other educational establishment or professional institute.

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Signed by supervisor to Michael Lawson:
Dr. Dealga P O'Callaghan, F.Arbor.A., CBiol., MIBiol., EurBiol., MAE.

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Michael Lawson

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Quotation

"When you set up any mathematical system, be it a classical dynamical system or the kind of thing used by the devotees of artificial life, you also implicitly set up a phase space. Phase spaces are big - they contain all possibilities, not just a selection. If the rule system is sufficiently rich - which basically means not horribly boring and obvious - then all sorts of possibilities lurk within its phase space. Now we begin to see the value of mutations in evolution. They don't just make evolution possible; they enable the system to explore its phase space. The states that the system is occupying today may change tomorrow. We also see the role of selection more clearly: It makes the exploration efficient. If all that happened were random mutations, the system would wander around its phase space like a drunkard, tottering one step forward, two steps back. Indeed the mathematics of random walks shows us that such systems spend an awful lot of time revisiting old haunts. With selection, however, bits of phase space that don't work, i.e. don't promote fitness, are eliminated. Selection helps the system to home in on the interesting regions of phase space, the places where useful things happen, the central features of the evolutionary landscape."

Ian Stewart
Life's Other Secret
Allen Lane (The Penguin Press) 1998

Career Synopsis

My name is Michael Lawson. I am an Arboricultural Consultant practising through O'Callaghan & Associates Ltd, Arboricultural, Urban Forestry and Biological Science Consultants. I am the Practice Managing Director with responsibility for 18 full and part time staff and associates. The Practice is accepted as an Assessor Member of the Institute of Environmental Assessment.

I hold the National Certificate in Arboriculture (NEB) with Distinction, BTEC National Diploma in Arboriculture and the Surrey County Diploma in Arboriculture. I am a Member of the Academy of Experts (MAE) and a Member of the Expert Witness Institute (MEWI). I am also a Law Society "Checked" Expert Witness.

I am a Professional Member of the International Society of Arboriculture (ISA) and a founder member of the United Kingdom & Ireland (UK/I) Chapter of that organisation. I am an Associate of the Institute of Biology and a Network Consultant of the Environmental Law Foundation. I have served as a Member of the Technical Advisory Board for the Higher National Diploma and the Honours Baccalaureate Degree in Arboriculture at Myerscough College, for which I provide lecture time to the Higher Education courses.

I have been involved in arboriculture for 14 years and have worked within the public and private sectors of the Arboricultural Industry both in the UK and the USA. I regularly provide Continuous Professional Development lectures for The Royal Institute of Chartered Surveyors, The Geological Society, the Institute of Structural Engineers, the Royal Institute of British Architects, the UK/I Chapter of the International Society of Arboriculture and the Arboricultural Association and Regional Branches.

I have authored / co-authored a number of scientific and technical papers on arboricultural subjects and I am regularly asked to speak at National and International Conferences and Seminars.

I have provided consultative advice and have been involved in television and radio productions for the British Broadcasting Corporation's Natural History Unit for BBC2, Manchester Unit for BBC1, Pebble Mill Centre for Radio 5, a private production company for Radio 4, The Television Education Network and BBC Radio Norfolk.

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Abstract

Trees have long been known to cause damage to man-made structures. Damage may be a result of secondary thickening leading to disruption or displacement of structures as trees grow. Alternatively, damage can be caused as trees distribute biomechanical stress as a result of wind loading, leading to stress forces being present within adjacent structures. Failure of trees or parts of trees can cause direct damage as they impact property. Trees can cause disruption to the reception / fidelity of radio and television signals by blocking a "line of transmission". Trees produce various exudates as a natural function of their physiology or indirectly as pests infest plant tissue leading to airborne "sap" which coats man-made surfaces often causing damage. Trees can cause differential damage to low rise buildings as a result of their ability to abstract water from soils through transpiration leading to changes in soil volume, in particular of clay soils, as water content within the clay fraction is reduced.

All of these modes of damage can lead to financial loss to the owners of the trees, third parties and buildings, and thus to the insurance carriers.

However, the losses incurred in respect of differential subsidence of low rise buildings constructed on clay soils, costs British insurers several hundred million pounds annually and it has been suggested that much of these losses are tree related.

This dissertation provides a comprehensive review of the evidence associated with the particular problems with subsidence of low rise buildings when caused or perceived to have been caused by volume change of clay soils as trees abstract water. A review of the available literature is presented and the key findings discussed. The dissertation provides the basis for consideration of the "Model Tree" and a theoretical working model is proposed, which can be measured against investigation and remedy techniques. An assessment of the availability of modern technical solutions to the problems encountered is discussed and the results of collaborative work undertaken is released.

Annex 1 released to the Institute's Examiner contains a collection of related papers, projects, systems and resource materials that are an integral part of the work described in this dissertation. They have been produced as part of my work within this field since the beginning of January 1996 and as such are integral to the project.

1.0. Introduction

1.1 The United Kingdom of England, Scotland, Wales & Northern Ireland is one of the most densely populated areas of the world. In all the population of the UK is about 65 million with 25 million residential homes and upwards of 25 million motor cars on a land area of 244,750 km^2*; Department of the Environment Transport and the Regions (1991).* The ratio of urban to rural population is one of the highest in the world and reflects the nature of the industrial development of the UK. The exact number of urban trees present in the United Kingdom is not known. However estimates made by O'Callaghan Associates Ltd using data available from various government and non-government agencies suggest that the number of truly urban trees is in the region of 100 million, possibly more. These data are supported by the results of surveys undertaken by Task Force Trees, which indicates that there are some 400,000 street trees and 6 million trees of other types (excluding woodlands) in London alone. This coverage of approximately 6 million trees within 33 Local Authorities, when put in the context approximately 550 Local Authorities nationwide, forms the basis of the conservative estimate stated above.

1.2 The UK and its human population is therefore very heavily urbanised and the interface between human artifacts and trees is not always an easy one. The fiscal, environmental and other benefits of trees have been well documented, *(Consolidating and Communicating Urban Forest Benefits - Davey Research Group - ISA Research Trust 1993).* However there have been few attempts to logically address the problems that trees can cause. Research is available and one of the key objectives of this dissertation is to collate the available data to facilitate assessment of the value of the existing work and provide analysis of the most positive areas for further research. This dissertation addresses the issues of damage to artifacts by trees with specific reference to subsidence of low rise buildings.

1.3 Indirect Damage

1.3.1 Indirect damage to low rise buildings is caused by tree growth and function. These processes cannot be directly implicated in the failure or disruption of a structure. Nevertheless, tree growth and function are important contributory factors in the problem, in which the other components in building failure combine to affect the damage. A common feature of the problem is that there is often no obvious or direct relationship between the tree and the damage to a building and there are usually a number of non-biological factors involved as well. The problem is therefore very complex in nature

1.0. Introduction (Continued)

1.4 This dissertation addresses the way trees indirectly damage buildings, in particular the damage associated with the abstraction of moisture from shrinkable clay soils by tree roots. This type of damage is one of the most challenging problems for arboriculturists. The damage is often many metres distant from trees and usually involves a variety of arboricultural, spatial, geotechnical, climatic, engineering and utility issues acting at the same time. The complex nature of the problem means that a wide range of professional disciplines must interact to address the failure, with all the usual problems of inter-disciplinary misunderstanding. The resulting mixture of prejudice, error, human nature, economics, law and politics naturally complicates the situation even further.

1.5 Subsidence of Low Rise Buildings

1.5.1 Subsidence damage is caused when there is movement in the soil below a building, which causes it to differentially displace and results in cracking and in extreme cases, major structural damage. This is differentiated from settlement damage, which is the result of downward pressure of the load of a building as it attains an equilibrium with its surroundings.

1.5.2 Subsidence damage to property in the United Kingdom is often said to be the single largest tree related insurance issue in this country, *Institution of Structural Engineers (1994).* The problem has been widely discussed among insurers, loss adjusters and structural engineers. However regardless of any published data, there is still a lot of confusion among the principal technical professionals concerned with the issue. The subject can be effectively divided into the following parts:

- The Value of Urban Trees
- The Climate
- The Clay Soils
- The Housing Stock of the United Kingdom
- Insurance and the Law within the United Kingdom
- The effects of vegetation on clay soils
- The Clay Soils, Vegetation and Climate Continuum
- Managing vegetation implicated in subsidence of low rise buildings
- The Available Research

The presence of trees can contribute significantly towards the problem of subsidence, especially in clay soil areas where the soil "shrinks and swells" according to its moisture content. It is estimated that around 60% of the nation's housing stock is built on subsidence prone clay soil; (*Mike Crilly, Geotechnical Officer, Building Research Establishment (BRE) - Personal Communication*).

1.0. Introduction (Continued)

1.5.3 Figures provided by the Association of British Insurers (ABI) for subsidence claims show that subsidence remains a significant issue, particularly when the relationship between the number of claims and the cost of rectification is explored: These are set out in the following table.

Year	Industry cost	No of Claims
1998	£375m	42,000
1997	£393m	45,900
1996	£333m	47,700
1995	£326m	44,700
1994	£125m	27,600

1.5.4 Such is the Government's level of concern about the impact of trees on buildings (particularly in respect of subsidence) that the Department of Transport, Environment and the Regions, (DETR) has recently allocated £638,000 towards research into the problem. We know from DETR research that approximately 20% of the nation's trees are street trees and it is estimated that approximately 60% of the nation's housing stock is built on subsidence-prone soil.

1.5.5 Over the past decade, subsidence claims have cost the insurance industry some £3.2 billion, (*Association of British Insurers*). Between 60% & 70% of these claims originated in areas with shrinkable clay soils, i.e. London and the South East and those generally found south of a line drawn between the Severn and Humber estuaries; (*BRE*).

1.5.6 During the period 1986 to 1992, settled and pending tree root claims for the London Boroughs alone stood at over £20m. This represented an average cost of £878,151 to each of the 23 Boroughs for which subsidence was a problem at that time. The average cost per claim was just over £4,000; *London Tree Officers (1995).*

1.5.7 More recently, an informal investigation (conducted by O'Callaghan Associates Ltd - February 2000) of three of the 23 London Boroughs, revealed that the average number of tree-related insurance claims per Borough for the last drought period (1995/96) was 168. Projection of these figures suggests that there were over 7,700 claims in the London area over that 2-year period. Assuming the cost per claim to be about £4,000, the cost of claims in London Boroughs for the 1995/96 period is estimated to be upwards of £31 million, which is greater than the previous drought period of 1986 to 1992 where the total was reported as £20 million over 6-years, London Tree Officers (1995).

1.0. Introduction (Continued)

1.5.8 Recent case law shows that the cost of individual claims can be significantly higher. In 1999, for example, in the case of *Delaware Mansions Ltd & Flecksun Ltd vs Westminster City Council*, the Council was held liable for tree root damage to a block of flats in Maida Vale which had been purchased by the plaintiffs in 1990. Although the case is due to go to appeal, the total cost to date is estimated to be in the region of £1m (with the cost of repair work amounting to over £570,000).

1.6 The Value of Urban Trees (Cost -v- Benefit Analysis)

1.6.1 It has long been acknowledged that mankind benefits from the presence of plants in urban areas. There are frequent references in historic documents to the magnificence of urban gardens. It is acknowledged that plantings represent a continuity for the urban population with its rural / agrarian heritage. This perception could well have resulted from the nomadic populations for whom trees represented a constant and renewable resource. As the scientific method of study became available the value of urban vegetation to the health and well being of human beings became more obvious. This scientific work continues to illustrate the dynamic nature of the relationship and interface between plant communities in urban settings. It is now established that urban vegetation plays an important role in urban sustainability and the socio-economic stability of communities*; Davey Resource Group, (1993).* However the presence of vegetation can also lead to a loss of local sustainability and this can impact macro-economic stability by complex feedback loops.

1.7 Climate

1.7.1 The climate of the United Kingdom is influenced by the weather systems of the Atlantic Ocean and the continental European mass. These two factors act on the geography of the UK in a dynamic and complex manner. However the west and north of the UK form an upland onto which weather systems from the Atlantic fall. The land to the south and east is generally at or very near sea level and its physical proximity to mainland Europe leads to a more continental type climate than in the north and west, with longer summers, average higher temperatures and lower average rainfall. Despite the Atlantic influence, the UK is relatively poor in water resources. River systems are short and are fed from a small watershed of upland areas. The large centres of population, particularly the Thames Valley, and low rainfall of the south and east combine to create a water poor environment. Counties such as Essex are actually classified as semi arid which is a strong indication of the critical role of water in these eastern counties. Additionally the impact of the dry summers from the 1970s onwards together with low winter rainfall has had an effect upon the volume of moisture in clay soils*; Marsh & Monkhouse (1992).*

1.0. Introduction (Continued)

1.7.2 The normal annual cycle of water loss from clay soils in the presence of vegetation is easily seen in the **M**eteorological **O**ffice **R**ainfall and **E**vapotranspirational **C**alculating **S**ystem (MORECS)*, (**Appendix 1**). The examples show water loss in millimetres beginning at the start of the new year when the soil is at field capacity, (FC = 0 - being a fully hydrated clay soil). The soils begin to dry as evapotranspiration accelerates through spring and summer, with peak values towards the middle and end of the summer. Autumn and winter rains usually begin to rehydrate the soils. If the overall rehydration level is less than the evapotranspirational loss, then a **S**oil **M**oisture **D**eficit (**SMD**) will develop. If this continues for a prolonged period then the SMD becomes 'persistent' and progressive ground movements can occur; *Lawson, (1993)*.

1.7.3 Comparison of different land use types utilising the MORECS system for the year 1990 clearly indicates the significance of vegetation to the abstraction of water from clay soils. The data at **Appendix 1** additionally compares three land use types including Bare Soil, Grass and Deciduous Trees. These are further supplemented by a full set of MORECS data for two 40km grid squares as an extended measure of the impact of open grassland on soil moisture deficits. The comparisons produce some interesting trends, as follows:

(i) **Bare Soil**

The maximum recorded SMD at any given point in the year is about 20mm. This clearly demonstrates that with between 150mm - 250mm of water potentially available to plants in any 1000mm of clay soil, the effects of sunlight alone on SMD are minimal.

(ii) ***Grass***

The impact of grass on soil moisture levels begins earlier in the year than deciduous trees and the resultant SMD can be significant. Grass is an effective living pump of water from soil.

(iii) ***Deciduous Trees***

A deficit persisting from the previous year is present for several weeks into the new year. The impact of trees begins later than that of grass and following "bud burst" it is July before trees overtake the water loss potential of grass. Trees transpire water against the inflow of summer rains, which grass does far less successfully. Deciduous trees maintain a very severe deficit until the end of the year.

1.0. Introduction (Continued)

1.8 Geology and Clay Soils

1.8.1 The UK has a complex and discontinuous geological structure. However the high and moderately shrinkable clay soils dominate the southern and eastern regions. Clay is a complex chemical medium, the result of geological weathering and prehistoric deposition. Its primary interest in biological terms relating to plant water use is that clay intercepts precipitation and binds water to its structure against gravitational energy. Plants are able to access a small percentage of the bound water and it is the shrinking of the clay volume as water is abstracted that can lead to movements in any structure founded on the clay material. It is important to appreciate that it is the volume of water in the soil that changes and not clay itself. Clay soils are found throughout the UK and the majority of these clay soils demonstrate an element of shrinkage when water is removed.

However various other factors must "converge" before the shrinkage becomes significant in structural terms:

- The clay must have a level of plasticity and cohesiveness;
- The soils must be capable of bearing vegetation which acts as a bio-mechanical pump;
- The drying forces must usually extend beneath the foundation level;
- Rainfall, infiltration and water bonding must be less than evapotranspiration for significant periods;
- Any structure built on clay soils must be susceptible to differential movements.

1.8.2 The clay content of soils has traditionally been tested for its cohesiveness by reference to its **Plasticity Index** (**P.I.**). The most commonly used measure being the 1 or 4 point Cone Penetrometer Method as described in **BS1377** Part 2, 4.1 to 4.3.5. This method analyses the soil's upper and lower plastic limits (i.e. too wet to paste, or too dry to retain a moulded form). The difference between these two limits is the notional **Plasticity Index.**

1.0. Introduction (Continued)

1.8.3 Clay soils are generally classified for comparative purposes based on their Plasticity Indices by the Building Research Establishment as follows:

	P I
Low Plastic:	<20%
Medium Plastic:	20-40%
High Plastic:	40-60%
Very High Plastic:	>60%

However the tests are of themselves crude and the value of these types of geotechnical tests in considering the relationship between vegetation and soils is limited; *(Crilly,. Pers. Comm.)*.

1.9 The Housing Stock

1.9.1 Within the United Kingdom the spatial arrangement of population centres has resulted in buildings located in areas that are prone to subsidence damage. The social, political and economic dominance of the south east of the country has resulted in a significant portion of the population living within this area. Housing densities and plot sizes often combine to produce an overcrowded environment in which the establishment and growth of urban trees is difficult. The presence of large numbers of houses built since 1900; land scarcity and post war rebuilding programmes; the comparatively recent development of building standards that take account of shrinkable soils, have combined to predispose the housing stock in the south east to differential structural movements on clay soils.

The chart at **Fig 1** represents a model of the interactions discussed above and in the context of the potential for a claim "event".

1.10 Insurance & Law

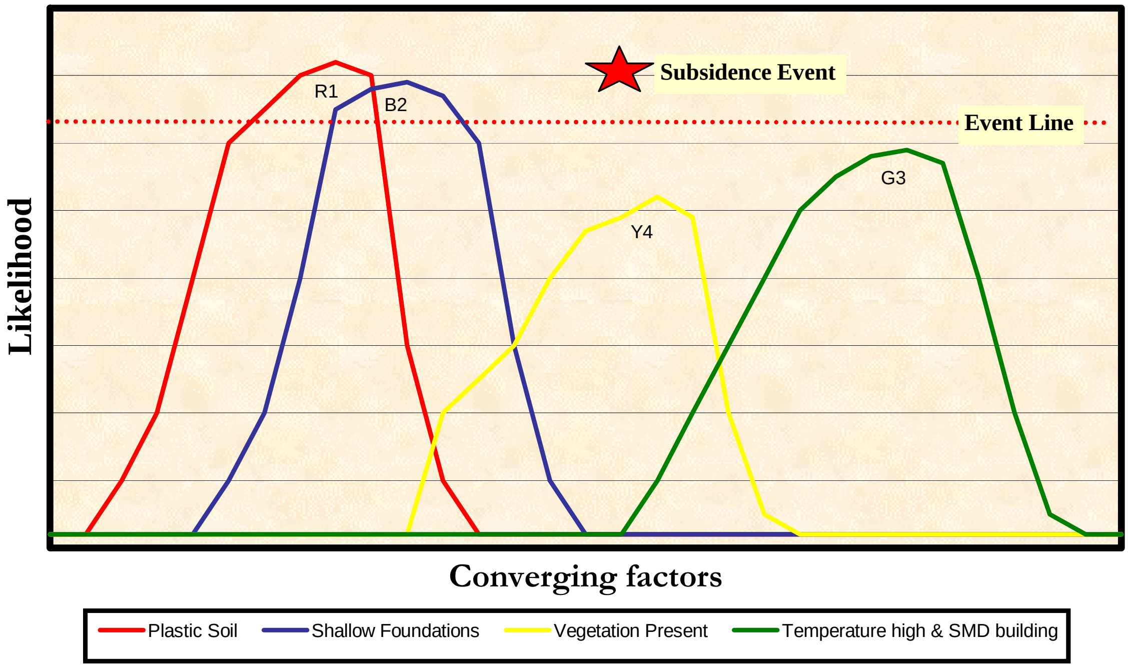
1.10.1 The law** of the United Kingdom is a combination of that passed by Parliament (Statute Law) and the accumulation of decisions in the Courts that is known as Common Law.

1.10.2 In respect of land, the evolution of the law relating to Planning, Management and Liability has resulted in a complex layer of insurance and legal frameworks.

****** **A full discussion of the legal framework is contained within the publication "*Amenity Trees and Insurance Issues - The Local Authority Perspective*" co-authored by M Lawson and is attached to this Dissertation; the Institute's Examiner has been provided with a copy in advance of this dissertation.**

Fig.1

Subsidence Claim



The model suggests that key factors converge to lead to an "event" in subsidence.

R1, **B2** are ever present, whilst **G3** and **Y4** are transitory.
Y4 increasing over a period of years and
G3 surging each year.
It is only when all factors cross the event line
that differential movements will occur.

Within **B2** engineered remedies apply and action on **Y4**
will prevent the development of **G3.**

2.0 Review of Available Literature

2.1 Areas of Search

2.1.1 The key objective of this area of search of arboricultural and engineering literature was to obtain information on the likely impact of tree roots and the influence of growth patterns on the soil environment.

2.1.2 However, given the very wide nature of research on trees which is undertaken world-wide by many different agencies and the myriad of scientific books and journals in which this research is published, it was considered necessary to search as large a volume of literature as possible.

2.2 The Scope of the Literature Search

2.2.1 This initial stage necessitated a broad appraisal of the factors which may impact on tree growth, not only in the short term but also for the longer term.

2.2.2 In view of this it was considered necessary to look at fundamental aspects of tree growth and any possible models, which could be useful in predicting long term impacts, therefore, the available relevant material needed to include theoretical as well as existing evidence.

2.2.3 A literature search was completed using the British Library Science Reference and Information Service. The main subject area was **The Rhizosphere** and the search strategy used was as follows:

2.2.4 Search in Commonwealth Agricultural Bureau, (CAB), Abstracts and Geobase (the database of geology and related earth sciences), for any reference mentioning the word **root** in the title, together with **Rhizosphere, Tree, Strata** or **Soil**. The key words **Shear Strength, Weathering, Temperature, Plasticity, Water Volume** or **Macropores** were also included. The search was restricted to articles written in English. The specific search retrieved **908** references, with many hundred additional papers collected over the last ten years as part of the OCA (UK) Limited library and of which over **100** papers, publications, digests and guidance notes are referenced within this dissertation. A full list of those relevant to this dissertation, is provided in the Bibliography.

The full text of any of these references can be obtained from the British Library. Additional papers have been obtained from the Arboricultural Advisory Information Service and from a programme of directed reading by the Supervisor to this Dissertation and the Research & Development Officer of O'Callaghan Associates Limited (Mr Les Round).

2.0 Review of Available Literature (Continued)

2.3 The review discusses subject areas under which tree roots and / or whole tree growth may have some impact on the soil, as well as fundamental requirements for growth, which may be affected by the environment, present or future.

2.4 A number of researchers have investigated the value of tree roots for improving the strength of soils; *Abe and Ziemer (1991).* The research showed that in shear tests with no roots, the maximum shear resistance occurred at 17mm of displacement. For all tests that contained roots shear resistance continually rose and the upper yield point was not reached even at 88mm of displacement. In Fig 10 of their paper an increase in the numbers of roots from 3 to 9 resulted in an increase of shear resistance at a displacement value of 80mm. The superiority of Pine roots to herbaceous plants in stabilising soil against slips and slides has also been demonstrated. Where it has been shown that with a maximum 75mm displacement, the shear resistance of Pine rooted soil was about twice that of non-rooted.

2.5 The interface between roots and the soil is of fundamental importance in terms of tree stability and the strength of the soil root bond from purely frictional considerations, might be expected to be about 20g / cm^2. The "pull out" resistance of single roots of field Pea (*Pisum sativum*) that had penetrated a few mm into a compacted clay loam (with a bulk density of 1.7g cm^{-3}) with a matrix potential of -0.3 bar, was of the order of 100g cm^{-2}, and where root hairs extended into the dense unsaturated soil, the values ranged from 300 to 600g cm^{-2}*; Waldron and Dakessian. (1981).* The cohesion capacity can be expressed as the sum of the cohesion capacity of the soil itself and the effects of the tree root system; the latter effect is proportional to either unit root weight or root cross-sectional area at the shear plane; *Endo, (1980).* This has been investigated in the field and the stability of slopes before and after removal of forest cover was assessed. Decay of tree roots subsequent to logging was found to cause a reduction in the shear strength of the soil-root system; *Wu, McKinnel & Swanston, (1979).*

2.6 In respect of the model tree, therefore, there is strong evidence to suggest that roots and especially tree roots have a major benefit in terms of soil & slope stabilisation. Trees effectively bind the soil together and total root mass is important. Thus the impact of any decision to remove trees on slopes must take this issue into consideration, regardless of any annual soil movements associated with clay shrinkage.

2.0 Review of Available Literature (Continued)

2.7 In addition to roots affecting the strength and stability of soil, they also have a chemical impact due to the release of root exudates and accumulation of acid humic substances through deposition of dead plant matter, with mineral weathering in the rhizosphere being higher than in the bulk soil. It has been found that ectomycorrhizal exudates proved to be effective weathering agents at low pH, i.e. 4.0, as opposed to humic material and non-mycorrhizal exudates. The most important agents responsible for mineral weathering are water and the hydrogen and hydroxide ions and (mostly organic) complex chemical compounds. Fungi, including ectomycorrhizal fungi, are able to produce certain organic compounds, especially hydroxamic acids, that are effective in chelating soil bound iron and aluminium. There is evidence that humic substances (and exudates from non-mycorrhizal tree roots) may inhibit the dissolution of minerals even under acidic conditions; *Ochs. et al.(1993).*

2.8 Plants release organic carbon into the rhizosphere, low-molecular weight free exudates, high-molecular weight gelatinous mucilage and sloughed off cells. Among the free exudates are citric and malic acids (which are important in uptake of phosphate). Many species characteristic of low nutrient soils produce 'cluster' roots; *Attiwell, & Adams, (1993). Smith (1976)* collected root exudates from a number of hardwood trees at Hubbard Brook, NE United States. He estimated that about 4 Kg/ha^{-1} of carbon was exuded, mostly as organic acids, predominately, Acetic, aconitic and oxalic acids. *Berthelin, J. et al. (1991)* describes the involvement of roots and rhizosphere microflora in the chemical weathering of soil minerals and that plant roots alone can take up and solubilize mineral elements. Weathering can be attributed, as demonstrated in experiments, to the production of acids and complex compounds by the roots themselves or by the association with micro organisms. *Lehmann & Cheng, (1988);* showed that phenolic acids are degradation products of lignin and possible plant foliage. Tests with ferulic acid showed that these oxidised products were rapidly bonded to surfaces containing Manganese dioxide (MnO^2). However, soil conditions may affect the quantity of phenolics liberated into the soil by plant roots and, therefore, they may have a role in soil formation and fertility with the potential for feedback between low soil nutrient conditions leading to high inputs of phenolics and still lower fertility; *Wareman & Mole, (1994).*

2.0 Review of Available Literature (Continued)

2.9 The influence of tree species on the chemical properties of the soil profile (in the upper horizons, i.e. 0-700mm) upon pH can have important effects on root and whole tree growth by its impact upon acidity. *Norden, (1992),* investigated this aspect below canopies of 100 to 150 yr. old individuals of **Fagus sylvatica*, ***Quercus robur*, ****Carpinus betulus*, +*Tilia cordata* and ++*Acer platanoides*, in three mixed deciduous forests. (*Beech) (** Oak) (*** Hornbeam) (+ Lime) (++ Norway Maple). The results identified obvious differences between the species in their ability to acidify the soil profile of brown forest soils, in terms of a decrease of exchangeable base cation pools, an increase of exchangeable aluminium and hydrogen ion pools, and usually a decrease in pH in the surface horizons. The effects were deeper under Oak than for other species.

2.10 In respect of the "model tree" this matter of exudates and impact on the soil environment is not that well understood, however, it would seem that roots do have a significant effect upon the weathering of soil in the rhizosphere and this could be part of the strategy utilised by some trees to exploit larger volumes of soil; see also *Kozlowski, Kramer & Pallardy, (1991).*

2.0 Review of Available Literature (Continued)

2.11 The uptake of nutrients / minerals is clearly important for growth, however, there is very little literature in the arboricultural arena which quantifies how this happens and the role played by different parts of the root system in biologically degraded, polluted and compacted urban soils.

2.12 Nitrogen allocation to fine roots is calculated as the difference between net mineralisation in the soil and nitrogen allocation to perennial wood and above ground litter. Although this method provides an estimate of the total carbon allocation it does not distinguish between the potential fate of the carbon, i.e. structural / tissue or respiration; *Hendricks, Nadelhoffer, & Aber, (1993).* The use of Fluorescein diacetate (FDA), to actively mark and distinguish between metabolically active and inactive roots suggested that although intact suberised roots do not fluoresce, if thin sections are examined fluorescence can be detected; *Fogel, (1990),* which provides some proof to the often quoted fact that suberised roots can be active resource take up zones.

2.13 The re-cycling of resources within the root zone is critical to understanding how the model tree copes with environmental changes. A number of researchers have considered the role of the fine root system in various aspects of the resource / energy budget of the whole tree. *Burke, & Raynal, (1994)* found that the fine non-woody root turnover was less important than litter fall in the cycling of Calcium and Magnesium and was similar to leaf fall in the amount of Nitrogen, Phosphorous, Potassium and Sulphur cycled.

2.14 The extent of the fine root system, the key biological principles and its role in resource re-cycling is poorly understood in arboricultural circles; *Lawson (1998).* However, in the ecological research literature there are a number of important papers on this subject. For example, *Fahey & Hughes, (1994).* report that fine root (<2mm dia.) biomass in mature hardwood forest was highest in June 1987 and was concentrated in the surface soil, with 43% in the forest floor horizons. After clearcutting fine root biomass accumulated rapidly in the regrowing forest, reaching 71% of that in the mature forest after only four years of recovery. Root growth was most rapid in June and July and the life span of these early season roots averaged 8 to 10 months. About 50% of the fine roots disappeared within the annual cycle.

2.0 Review of Available Literature (Continued)

2.15 In respect of the model tree the above seems to indicate a significant role for the fine system in tree nutrient cycling. In addition it is also clear why the level of root exudates is so high. Also in terms of soil reinforcement, given that the life of fine roots is limited and that the roots hairs are critical to the root/soil bond, the importance of healthy soil and trees for continuity of a fine root population is a clear need. The use of computer models to simulate root growth may provide a useful research tool for designing and interpretation of experiments in the field. The use of core samples using a variety of techniques is discussed by *Mackie-Dawson, & Atkinson, (1991),* who consider that the use of simple core sampling over time provides a good estimation of the fine root activity. Their data strongly suggest that fine root growth is much more dynamic than has previously been identified. In terms of the Model Tree it would appear that we can begin to allocate specific quantitative data to this part of the model. These data have a direct impact on understanding of why there are differences in trees, both within and between species, and in their subsequent ability to be implicated in subsidence of low-rise buildings.

2.16 In respect of subsidence of low rise buildings, data has been available for many decades. The following quotation is from *Ward, (1947):*

" Subsidence causes damage to buildings and the trouble, which appears to be largely confined to south east England, is widespread in London suburbs."

Ward, (1947) also commented as follows:

" Three salient facts are noted irrespective of the age of the property:

- **All the properties were founded on a heavy clay with large shrinkage capacity.**
- **Nearly all the cracking has occurred in the last six years.**
- **About 90% of the properties had fast growing trees or shrubs nearby."**

2.17 This paper is an interesting assessment of the issues and clearly demonstrates that these problems have existed for some time. Ward's comments provide an interesting historical context. More recently, *Biddle, (1979),* stated:

"A hardening of attitudes by insurers, their agents and insured, as well as the Courts is due to changes in policy coverage during the early 1970s, alarmist press reports, recent legal precedent and the severe drought of 1975/1976. Differential movements will stress a building and may cause cracking. One potential method of controlling water demand is by species selection. The obvious lesson to be learnt is to control the growth rate and thus the water demand by pruning to suit the vulnerability of the adjacent buildings."

2.0 Review of Available Literature (Continued)

2.18 Subsequently, Biddle undertook research on behalf of the National House Building Council, (NHBC), which in 1986 resulted in a set of recommendations, for builders, that provide guidance on the construction of foundations when building near trees. Since 1986 there have been a number of updates of those recommendations, the most recent being, the NHBC Standards (1992); Chapter **4.2**: *'Building Near Trees'.* This is essentially a design guide for builders which uses soil plasticity ranges, cross referenced with geographic location and a rating system for tree water demand to calculate depth of new foundation. By following this guidance, builders obtain the NHBC guarantee for their buildings.

2.19 It is clear from Biddle's work that the model developed is based on soil moisture measurements made with a neutron probe together with consultant support of experienced structural engineers, *Biddle, (1986).* This facilitated the production of an empirical model of tree water use, which effectively drives the tabulated rating of tree species by water demand contained within the NHBC system. There are flaws within the model's technical base. For example, *"Eucalyptus"* is not a species as defined within the NHBC and many other tree species have never been subject to research into their water use. The simple dynamics of the model suggests a cost benefit analysis of the likelihood of a damaging subsidence event based on depth of traditional foundations, rather than any biological assessment of the trees or their physiological processes.

2.20 Dr Biddle has published a number of other papers on the subject, e.g. *'**Tree roots and foundations'*** AAIS 142-98EXT *Biddle (1998)*, a model for the investigation and management of tree related subsidence events and more recently a two volume work entitled ***'Tree Root Damage To Buildings'*** *(1999).* I have critically reviewed the latter on behalf of the Arboricultural Journal, *Lawson (1998)*, however a summary is set out below.

"Volume one of the two volumes deals with important issues of investigation, interpretation, remedy, research and policy, associated with trees and the damage they can cause to structures. The introduction to the Preface suggests that *"Trees are undoubtedly the biggest cause of subsidence".* "Subsidence" being the term often associated with all forms of ground settlement not associated with loading of the soil by structures. It is further suggested within the Summary of Chapter 1 that, *" … trees are involved in at least 80% of cases of subsidence claims."* However on page 3 the Author states, *"When damage does occur there is a tendency to assume that an adjacent tree is the cause".*

2.0 Review of Available Literature (Continued)

The review continues

The original statements on the relative percentage cases of tree related subsidence were first published by the Institute of Structural Engineers, (ISE) in 1994, ("Subsidence of Low Rise Buildings"). Various figures are suggested within this publication, i.e. on page 37 it suggests 50% - 60% while on page 57 a figure of over 80% of cases are thought to be tree related. However care must be exercised in the use of a broad term like "subsidence" when what is meant is "tree related subsidence cases". Vegetation is certainly a significant factor in subsidence cases involving cohesive soils, however the various statistics needed and the formal verification of these statistics have not to my knowledge been made available to the general professional community by the insurers. In this instance no reference is offered. Subsidence is associated with settlement of soils involving amongst other things, mining subsidence; slip and creep; fill materials; peat soils; old refuse and landfill sites; ground above underground water sources; ground above existing/historic services; pits of all types; old foundations or other concealed construction; clay soils with vegetation and / or areas liable to flooding and wetting. It seems central to the thesis of the ISE publication that in the ISE's opinion, over 80% of all subsidence is tree related.

Chapters 2 and 3 introduce the tree and root system. The language moves from the highly technical in respect of the expected baseline knowledge of the allied professions, to the overly simplistic and obviously flawed in respect of the trained biologist, forester or arboriculturist. If the intention of the author is to challenge some basic principles of plant biology then certainly statements such as: *"The distinction between xylem and phloem applies to all woody tissue (i.e. twigs, branches, trunk and roots) all of which have an essentially similar structure." "Water transport…..only occurs in the outermost annual rings, mostly in the current seasons ring…….The heartwood becomes totally non-functional….."* The statement within Chapter 2 on the similarities in tissue structure cannot be reconciled with the statement within Chapter 3, *"as the functions of the two systems are so different and as they develop in such different environments, it should not be surprising that their development, morphology and physiology should reflect these differences".* Additional observations, *"the roots are supported by the soil so that gravitational effects are of no significance beyond the main structural roots…"* or the laboured analogy that tree root systems are like a wine glass, are unhelpful and could certainly not be considered accurate or helpful by arboriculturists. The overall impression of the tree biology sections is of a confused and confusing summary of accepted (or not) current thinking.

2.0 Review of Available Literature (Continued)

The review continues

Chapters 4 - 16 deal with the soil, soil moisture deficits and thereafter increasingly focus on trees and buildings, site investigations and methods used. Certainly Dr Biddle's understanding of soil geotechnics appears sound and I found these sections interesting and informative, although poorly placed to judge the accuracy of the content, most of that described accorded with generally accepted principles. Importantly within Chapter 9, it states, *"In any analysis of this sort it is difficult to know whether the response by the experts reflects their own practical experience or whether they are prejudiced by previously published data".* (Caution indeed.) The discussions within Chapter 9 seem far too certain in ranking and rating tree species by the various methods and the caution that, *"it must be recognised that there is massive variations between individual trees of the same species".* Dr Biddle also sees environment and not genetic factors as of primary importance in understanding soil/root interactions.

The general view proposed by Biddle is that pruning is not a universal panacea for subsidence problems and that there are a variety of problems associated with this remedial option, however the publication certainly does not rule out topping mature trees and offers many examples of pruning practice that will certainly maintain the myth that urban forest cover and soil water loss can be regulated by heavy pruning regimes.

Figure 17.1 suggests that large cycles of movement can be rendered harmless or negligible by judicious topping. Figure 17.7 illustrates a mutilated tree, heavily topped as a remedy. I can only sum up my concern with the remedies suggested by quoting Dr Biddle direct.

" BS3998 1989 includes various comments on the frequency and severity of pruning, for instance recommending that……pollarding should not be used on trees which have not previously been pollarded. Whilst caveats of this sort are correct for general advice, it is essential to ensure that the work which is undertaken is sufficient to achieve the desired objective. If the means justify the ends, severe pruning, in excess of the ideal, may be required and justified".

The use of pruning of the type proposed by Biddle is at variance with the advice of the industry standard (BSI 3998 Tree Work) with all other published standards for tree care and his views have certainly helped lead to a policy for tree pruning with the key standards applied by our municipal authorities to the detriment of thousands of miles of the UKs highway tree stock."

2.0 Review of Available Literature (Continued)

2.21 The Building Research Establishment (BRE) has also produced a number of publications, which are germane to the discussion of subsidence of low rise buildings.

For example:
Digest 298 The influence of trees on house foundations in clay soils (1999)
Digest 240 Low Rise Buildings on shrinkable clay soils : Part 1 (1993)
Digest 241 Low Rise Buildings on shrinkable clay soils : Part 2 (1990)
Digest 251 Assessment of damage to low-rise buildings (1990).
Digest 268 Common defects in low rise traditional housing (1990).

Additionally the work of Cutler & Richardson (1989) supplies the only consistent and qualitative research into reported tree root presence in spatial terms from reported subsidence cases.

2.22 It is clear that as mankind has built shelters (houses) since ancient times, that buildings are important to society. In modern culture and society, cracks and distortions can spoil man's enjoyment of a building. Where the cracks and distortions arise from differential subsidence, it is rare for a building to become uninhabitable as a result. Where the structural integrity of a building is compromised, it is also rare that its weather tightness fails, yet the nature of property markets means that cosmetic damage, i.e. cracks of only a few millimetres, can cause a drop in the market value of a property of tens of thousands of pounds, such that a property can become blighted. Given that there are established methods for establishing the causes of such differential distortions, it is strange that there is so much confusion surrounding the issue of 'tree related subsidence'.

2.0 Review of Available Literature (Continued)

2.23 There are many myths regarding the extent of tree root systems. *Schnelle, Feucht & Klett, (1989)* provided data which suggests that the maximum root spread ranged from 1.7 times to 3.8 times the radius of the branch spread, depending on species, and that deep root systems are the exception rather than the norm with little root growth occurring below 1.30m. However, others have shown that in nature whole plant processes may have a more powerful influence on root growth and orientation than processes at the level of the individual root; *Kramer & Kozlowski, (1979).* Root nutations are poorly understood, but some show an unpredictable (stochastic) pattern of tip movement; *Barlow & Zieschang, (1994).* Modeling of root growth using computer algorithms, *Fitter et al (1991)*, simulated the growth of a root system and its exploitation of the soil, calculated the relationship between its exploitation and its architectural characteristics. These studies and those regarding fine roots discussed above clearly point to a much more dynamic situation in which the main bulk of the root system is found within the canopy, particularly in mature trees. However, there is no doubt that a small proportion of roots do travel long distances through the soil, both horizontally and vertically; *Cutler, et. al. (1989).* This latter aspect is of particular importance in relation to subsidence.

2.0 Review of Available Literature (Continued)

2.24 The compression caused by roots also forms channels in the soil which may be of considerable significance for the long term improvement in soil structure. The very process of root growth assists in the formation of micro and macro pores in the soil. The pores produced by roots are likely to have more continuity and less discontinuity than inter-aggregate pores. Furthermore because roots are most likely to follow planes of weakness in clay soils, the resulting pores are more likely to link with the natural structural voids. Hence such pores may well drain better and so provide a better environment for subsequent roots to exploit; *Goss, (1991).* Extraction of millimetres of water per day by vegetation including trees, leads to repeated drying and wetting of soils. The evidence suggests that in soil of poor structure the wetting and drying improves soil stability. Probably the most important aspect of the removal of water by plant roots is shrinkage leading to cracking; *Goss, (1991).*

2.26 In addition to the extent of root growth there is some confusion regarding the longevity of non-suberised roots. Research suggests that root longevity and mortality may be significantly plastic in response to changes in soil resource availability, as is well known for root proliferation*; Pregitzer, Hendrick & Fogel, (1993).* Others have found that species may have different strategies for dealing with changes in available water. *Cermak, Matyssek & Kucera, (1993),* provided evidence from experiments on irrigation of drought stressed Beech in which they found that "*not all xylem vessels are blocked by cavitation and not all roots stop absorbing water until the trees lose more than 90% of their leaves. However, leaf loss and tree decline may proceed rapidly on clay soils that have limited hydraulic conductivity, because of severe local drought stress in trees with poorly developed roots systems*".

2.27 Mechanical impedance is experienced to varying degrees by virtually all roots growing through soil. If continuous pores of sufficient diameter do not already exist, a root tip must exert a force to deform the soil. This process may decrease root elongation rates significantly; increase the root diameter and change the pattern of lateral root initiation. Penetrometer resistance is currently the best method for estimating resistance to root growth in soil. However, there are many limitations, i.e. that roots are not steel pins being pushed through the soil but are covered in mucilage, and have the ability to exert drying forces and can rotate their growing point to find the line of least resistance. It has also been established that root elongation rate is progressively decreased by increasing mechanical resistance and ceases at root forces of about 1 MPa; *Bengough & Mullens, (1990).*

2.0 Review of Available Literature (Continued)

2.28 The maximum bulk density permitting root penetration could vary from 1.46mg/m^3 in clays to 1.75mg/m^3 in sands and compacted soils with a high clay content and high bulk density providing a significant barrier to root growth. The fine roots, 1mm to 60 microns in cross section, cannot penetrate into rigid pores with diameter less than that of the expansion zone of the root. Roots are also unable to decrease in size to enter a pore; *Suter, Luxmoore & Smith, (1993).* These matters are greatly complicated in the very fine soils and analytical tests are not well developed; *Tariq, Ata-ur-Rehman and Durnford, D.S. 1993.*

2.29 Perhaps the most misunderstood aspect of tree growth is that of "water extraction". Seasonal water use is related to the availability of soil water at the time of planting, seasonal precipitation and root penetration. The amount of water retained within the tissue of agricultural plants is generally less than 1% of the total evaporated during a normal growing season. Evaporative demand effectively reduces water availability by increasing soil suctions adding to resistance to water transport; *Jensen, (1968).* Jensen's work provides an excellent review of methods available to assess water loss from forest soils and the results of a wide range of theoretical and quantitative testing. Trees are effective mechanisms of drying soils with transpirational loss in the region of 4mm of soil water per day in warm dry conditions. Trees form an effective "umbrella" to summer recharge of soils by rainfall with coniferous trees intercepting and allowing evaporation of as much as 3 times the intercepted rainfall of deciduous trees; *Crafts, (1968).*

2.30 Water stress has significant implications for all plant biological processes and regulates almost all plant physiological activity. As a plant transpires a lowering of the water potential in the mesophyll cell walls is transmitted progressively throughout the apoplast system to the cell walls of the root hairs. The mass flow of water from soil to root, shoot and atmosphere is adversely impacted by the low water conductivity of unsaturated soil; *Zahner, (1968).* It is an established fact that apical, radial and reproductive growth of trees is highly correlated with environmental water stress; *Kramer & Kozlowski, (1979).* Roots suffer as a sink for photosynthates by virtue of the long distances from source to sink, however they benefit from proximity to soil water in relation to shoot material.

2.0 Review of Available Literature (Continued)

2.31 Water potential in roots seems to be constant, in a wide range of species, at around -0.2 MPa; *Pritchard, (1994).* This suggests that there is little difference between species in their ability to generate sufficient suction forces to overcome soil suction pressures. For example, it is suggested by the author that Beech and Oak both have very similar capabilities to extract water. Therefore the '*high water use*' of Oak, NHBC (1992), is not related to any ability to extract more water from a given volume of soil but rather to the plant strategy for exploitation of Resource Depletion Zones (RDZs), *Atkinson et al (1991)*; and subsequently of the water resources deeper in clay soil. Factors which alter root growth, such as lower soil temperatures, must also affect solute import making separation of the two processes difficult. Perhaps a key paper is that of *Gallego, et al (1994).* This work reports upon water use by Oak growing in two extremes of a rainfall gradient. In response to progressive decrease in soil water, no substantial changes were recorded in pre-dawn leaf water potential or in stomatal conductance. This suggests a non-conservative water use, with a tendency to use up water reserves from progressively deeper soil layers thereby avoiding marked stomatal closure.

2.32 The above provides a number of pointers for the "Model Tree", in particular that it is tree rooting strategies for resource capture which drive the response of roots to changing water status of the soil. The exploitation of the soil may be restricted by physical and chemical aspects but roots are plastic in their response to these, which may enable the resources to be accessed. There is potentially a much larger reduction in growth of deep rooting species, in response to limited space via restricted rooting, than in less deep rooting species; *McConnaughay, & Bazzaz, (1992).*

2.33 There are other aspects of the soil environment which have an impact on root growth. *Thompson & Troeh, (1978)* report that total pore space is a poor measure of aeration because the water content is variable. The finer-textured soils generally have the highest percentage of total pore space, but they also hold most water. Some Clay B horizons have nearly 60% pore space but are so poor in oxygen that it is inadequate for good root growth. The oxygen supply is likely to be inadequate for good root development whenever the soil holds so much water that it has less than 10% air space at field capacity. In fact *Hodge, (1991)* reports that damage to plant roots occurs at O_2 levels of less than 10% and growth usually stops at less than 5%.

2.0 Review of Available Literature (Continued)

2.34 Changes in root growth correspond to variation in soil temperature and moisture; *Teskey, & Hinckley, (1981)* reported that the rate of root elongation decreases during a summer drought and growth ceased in September. Root growth resumes shortly after rainfall events in October and elongation decreases again in late autumn and early winter in response to lower soil temperatures. The number of growing roots and root intensity showed peaks at 8°C. This coincided with two distinct and short time periods: ***a)*** March 18 to April 6, which immediately preceded bud burst, and ***b)*** November 1 to 16, which followed leaf fall. Temperatures which produce the highest rates of root growth of deciduous trees under non-limiting moisture conditions are reported to be greater than 20°C. However, optimal ecological root growth was found to be 17°C. Changes in the number of growing roots, which were not strictly controlled by temperature or soil moisture, seem to be the key to the survival of white oak on dry sites.

2.35 For the 'Model Tree' it seems that the overriding requirement for optimal root growth is soil bulk density and the size and connection of pore spaces. Increased soil temperatures do have an impact and some plants seem to cope with changes in water potential. Restriction of root growth by chemical manipulation of the soil may be a possibility for further evaluation.

2.36 The potential impact of climate change on forests has been subject of much research, which has been reviewed by *Krauchi, (1993)*. In addition to a comprehensive review, Karuchi sets out the research needs and the likely effects of a doubling in atmospheric CO_2. In the Carbon 3 group of plants (trees of temperate regions included) it is estimated that a doubling of CO_2 concentration, with all else constant, will increase growth and yield by about 34% +/- 6%. If the climate warms by 3°C the relative increase in plant growth caused by CO_2 doubling could be in the region of 56%. Changes in growth are likely to affect evapotranspiration through changes in plant size, particularly leaf area and root length (area), resulting in a better access to water and mineral nutrients. Temperate forest trees, most of them having the C3 pathway, are expected to out-perform in competition with C4 plants such as grasses. It is not clear whether the short-term responses can be sustained in long-term perennial growth. Theoretically, a rise of 1°C in mean annual temperature could cause a northward shift of each vegetation zone of about 200 Km and an upwards shift of 180m. Past records of tree line elevation suggest a 100m shift for each 1°C increase; *Krauchi, (1993).*

2.0 Review of Available Literature (Continued)

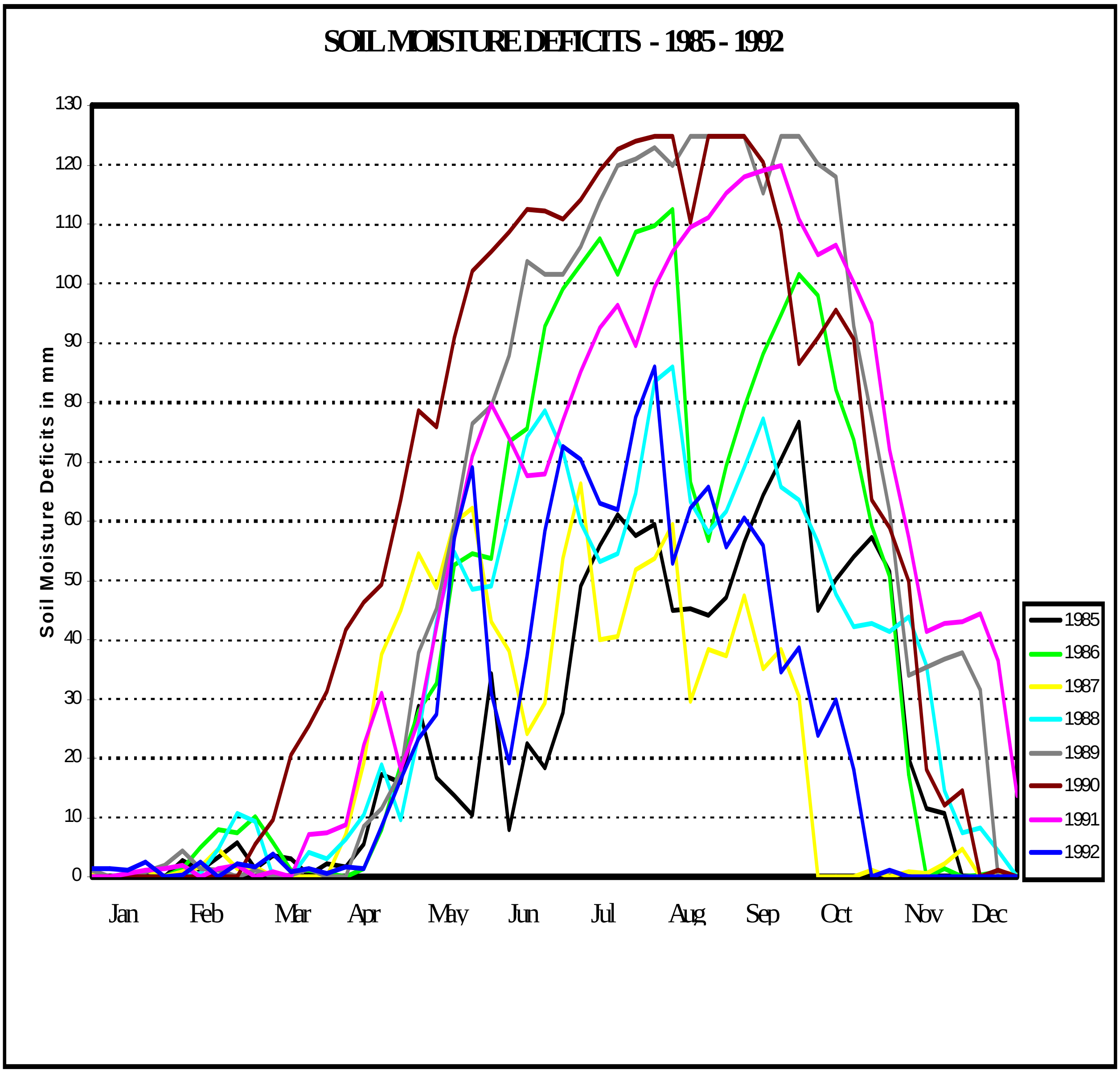
2.37 Plants do not draw water only from the immediate vicinity of their actively absorbing roots. As extraction of the water adjacent to a root proceeds, a depletion zone similar to that for mobile ions develops, causing water to flow over a distance of at least several millimetres from the bulk soil to root surface. This zone may extend for 1m when developed over a complete season; *Crilly, (1999) Pers. Comm.* However, at the same time, the withdrawal of water from the larger pores reduces the volume of soil through which flow can take place. For example, a sandy loam soil with a hydraulic conductivity of 6cm per day, at a matrix potential of -5MPa fell to less than 10^{-6} cm day at -1.5 MPa, i.e. the decrease in soil pore size increases the pore pressure; *Fitter, & Hay, (1987).*

2.38 The availability of soil water to trees is related to climate and rainfall and must be considered in relation to the meteorological records. The impact of climate on soil moisture deficit has been considered in detail; *Lawson, (1993).* The Meteorological Office has been recording Soil Moisture Deficits (SMD) throughout the United Kingdom since 1960 and has constructed an extensive database on rainfall and evapotranspiration in relation to soils and SMD. This is known as the **M**eteorological **O**ffice **R**ainfall and **E**vapotranspiration **C**ollating **S**ystem, (**MORECS**), and was initially undertaken for agricultural purposes.

2.39 These data provide an invaluable picture of the changes in SMD over time providing records in both temporal and spatial dimensions. The examples at **Fig 2** illustrate results from locations within the Cheshire Plain. It is accepted that there are in excess of 120mm of water per 1000mm of clay soil available to vegetation (including trees). Therefore, when deficits approach this level, they are severe. (A fuller discussion is set out in **Appendix 1** of this Dissertation).

2.40 On some of the more shrinkable and impermeable clays, the deficit could persist for a number of years, being compounded by continuing drought and taking many years to rehydrate. In this scenario, ground movements due initially to subsidence and laterally to heave could occur.

Fig 2



The normal annual cycle of water loss from clay soils in the presence of vegetation is illustrated within this chart. The examples indicate water loss in millimetres beginning at the start of the new year with the soil at field capacity (FC=0); the soils begin to dry as evapotranspiration accelerates through spring and summer, with peak values towards the end of the summer. Autumn and winter rains will then usually begin to rehydrate the soils. If the overall rehydration level is less than the evapotranspirational loss, then a persistent soil moisture deficit will develop and if this continues for a considerable period then progressive ground movements will occur.

2.0 Review of Available Literature (Continued)

2.41 Soil moisture deficits can occur with or without trees. Other vegetation such as woody shrubs, grass etc, can and do contribute to SMD. Trees can add to the severity of the SMD due to adaptive pressures leading to deep rooting and possibly to hydraulic lift; *O'Callaghan & Lawson (1995).* The amount of water available to roots may be higher in clay soils than the models predict because readily available "free" water and roots both appear to concentrate in small areas, excluding the major part of the soil mass; *Bouma & Dekker, (1978).*

2.42 Attempts to accurately measure water use have been undertaken using the neutron probe; *Biddle, (1999).* However, comparison of neutron probe count ratio rates measured at 10cm depth, with bulk soil water contents measured 3-5m away from the access tube, confirmed that in swelling/shrinking clay soils, recharge may be over estimated; *Jarvis & Leeds-Harrison, (1987).* A more recent method of measuring soil water is Time Domain Reflectometry (TDR); *Whalley, (1993).*

2.43 The distribution of carbohydrates for wood production was considered *by King, (1993).* This work showed that production of wood by individual trees was maximised by higher allocation to roots. This is because large root systems enhance the ability of individuals to compete for nutrients and that the optimal fine root allocation was less than 5% of total production but rose to 30% as nitrogen became limiting.

2.44 A number of authors have put forward different models for various aspects of tree growth, some of which are reviewed here. For example, *Vertessy, et al. (1995),* proposed a relationship between the sapwood area, leaf area and the rate of transpiration. The study did find a strong correlation with these factors. However, the study only looked at transpiration during the spring when water is unlikely to be limiting. Thus this type of model only considers 'potential' transpiration rather than what happens to transpiration rates when soil water potentials increase and stomatal control operates to limit water loss.

2.45 *Lindsey & Bassuk, (1992),* looked at a range of tree species and the relationship between leaf area and transpiration volume. Table 1 of their results shows that canopy area and water loss were not correlated with total canopy area but with mean area per leaf.

2.46 *Robinson, (1989),* produced data which show a model of fluxes across an ecological plane between plants and their environment.

2.0 Review of Available Literature (Continued)

2.47 *Watson, & Casper, (1984)* suggested a model that considers the way in which carbon is allocated to various sink points based on the carbon balance between different parts of the tree. They proposed that the volume of resources being transported determines the direction of transport and at which point resources are no longer provided to ageing parts of the system.

2.48 *Habib & Lafolie, (1989)* considered a one dimensional model of water absorption efficiency; it is suggested that the model could be used to identify the location of active roots in the soil profile. This is a purely mathematical model that lends itself to computer simulation.

2.49 *Goss, (1989)* showed the interactions between root growth and functions and soil conditions. This model illustrates how the root system can have considerable impact on soil structure and particularly on water availability / storage. Root elongation and radial expansion can produce new channels in the soil and these processes, together with uptake of water, can cause compression, shearing, and dehydration.

2.50 The removal of leaves is considered by various authors as important in reducing water use Biddle (*1999*). *Singh & Thompson, (1995)*, looked at the impact of removal of 3 different levels of leaf cover. Within 24 hours of lopping transpiration decreased and water potentials increased. The lopping effect lasted for some 42 days. Only in the heavily lopped trees, i.e. crown removal of 80%+, was there any reduction in growth. These results are supported by data recorded by the BRE during an 8-year investigation in the City of Westminster, *Crilly (in preparation),* which show that heavy pruning events caused only very short curtailment of tree water use for a single season, followed by a large increase in soil water use over the next 7 years.

2.0 Review of Available Literature (Continued)

2.51 The principal environmental factors that influence photosynthesis of trees are light, temperature, CO_2 concentration in the air, water, soil fertility, atmospheric pollutants and applied chemicals, insects and diseases. The rate of photosynthesis of the shade grown leaves of the European Beech is four to five times greater than those of sun-grown leaves when measured at low light levels; however, this seems to be opposite in evergreen species; *Overdieck, D. and Forstreuter, M. 1994*. The reasons for this seem to be related to the efficiency of the photosynthetic units at differing levels of light intensity, i.e. sun leaves operate more efficiently at high light levels and poorly at low light intensity; shade leaves have the opposite response. The ability of shade leaves to change their morphology following exposure after thinning or removal of sun leaves seems to be very limited. However, new leaves will adapt to the existing situation, i.e. if exposed to high light intensity they will develop as sun leaves; *Kramer & Kozlowski, (1979).*

2.0 Review of Available Literature (Continued)

2.52 Stemwood production by a population of trees is largely determined by leaf area index and the rate of production per unit leaf area; *Smith, & Long A (1992).* Furthermore, the high leaf area efficiency of small trees may be related to changes in carbon allocation associated with age and density, as small trees had higher foliar biomass compared with total crown biomass. By contrast, proportionally less of the total crown biomass was allocated to foliage in stands of large trees. This may suggest that trees which have been heavily pruned to remove a large amount of non-productive biomass will have more efficient leaf area efficiency; *Smith, & Long A (1992).*

2.53 *Haddad, et al. (1995)* suggests that the regular pruning of trees to create pollards has been practiced for hundreds if not thousands of years. This study investigated how pollarding had affected starch reserves in some 60 to 70 year old London Plane growing in an urban area of France. The study considered the existing evidence, which identified that the pollarding resulted in the storage of starch in the junctions of branches and at the base of the pollard points. This study found that in newly pruned trees starch concentrations were higher in large branches and even 2cm to 3cm branches compared to unpruned trees. Thus pruned trees have starch reserves much closer to the point of re-growth than unpruned trees. This redistribution of resources allows a much faster response to further pruning following the initial lopping. This provides further evidence for the Dissertation Model and supports it in regard to what has been recorded by the BRE site in Westminster; (paragraph 2.50 above).

2.54 Extension growth and branching probably represent alternative strategies in the exploration of soil volumes. A linear system cannot make optimum use of resources encountered and conversely, a clumped system cannot discover new resources. The effectiveness of all root systems must depend on the balance between canalised genetic control and mechanisms that control the plastic response to environmental signals; *Harper, et al (1989).* It is widely known that the gross morphology of roots and root systems differ in different tree species; *Atkinson & Last, (1995).*

2.55 *Phillips & Ehleringer, (1995),* showed by using the naturally occurring stable isotope of oxygen (delta oxygen 18) trees were using water from deep in the soil profile and not making any use of summer rainfall in their transpiration stream. This provides evidence for rooting strategies which are evolutionary adaptations for avoiding drought and the mechanism for which species, such as Oak, extract water from clay soils at depth.

2.0 Review of Available Literature (Continued)

2.56 *Moreno et al. (1996),* showed that transpiration rates for various tree species have been well documented and it is clear that the potential rates for "high water" demanding species and "low water" demanding species are very similar. This study provides evidence that some species are more "water efficient" than others. The study provides evidence that even when irrigated the Olive did not increase its water use. This supports the proposition that 'water demand' is simply the *'minimum amount of water a tree requires to keep its physiological processes functioning'*; *Lawson & O'Callaghan, (1995).*

2.57 *Smith, et al. (1997),* reviewed the proposed strategy of certain tree species, to absorb water from deep in the soil and even in some cases the permanent water table and then transport this water to the surface layers of the soil as postulated by *Dawson, T. E. (1993 and 1996).* This has become recognised as an important mechanism of transfer of resources. However, *Smith et al. (1976)* suggest that some species may use the opposite strategy of transferring water down to lower profiles in order to provide the tree with a reserve of water. This research has been carried out only on young trees in the tropics and may not be applicable to temperate regions.

2.58 There have been various models put forward for water resource capture, *Binns (1980). Helliwell (1993)* put forward the model which proposed that trees do not make use of the permanent water table but use the water stored in the soil at field capacity. However in separate studies *Dawson, T. E. (1993 and 1996)* suggested that strategies for capture of water at depth do exist. The work of Dawson found, that while the model for local soil water use was true for Sugar Maple in their early growth phase, by the time they approached maturity they were in fact using the water table for all their transpiration needs. This suggests that once trees have reached maturity and have established an "underground ecosystem" which they have filled with fine roots and efficient transport routes, they do not waste energy in competing for resources outside of that "ecosystem". This provides a rationale for why when trees are topped they do not immediately reduce the size of the root system in which they have invested so much energy and that only over time would that system reach a new equilibrium for its resource and transport needs.

2.59 *Marshall, Patch, & Dobson, (1997),* discuss the various means by which trees may cause direct damage and possible measures to prevent it. The criteria for successful root barriers are summarized. They go on to discuss the limitations of such root barriers but consider that these are acceptable if they allow the tree to be retained for a few more years. However, they do not consider the implications for the owner or those recommending the solution when damage occurs again; see also *Nicholl & Armstrong, (1997)*

2.0 Review of Available Literature (Continued)

2.60 *McPherson, et al. (1995),* compared the costs of damage to sewer and pavements in 15 cities in the USA. A number of approaches to damage prevention / limitation were used, including chemically (Copper) treated root barriers, foam layers under pavements and air gaps between the soil and pavement.

2.61 A key publication supporting this Dissertation is 'The Physiology of Woody Plants', *Kramer & Kozlowski, (1979).* This work provides many parts for a Model that can be constructed. While it is extensively quoted within this Dissertation, there are a number of key principles that are highlighted:

2.61.1 ***Water Transport in the Tree***

There is a relationship and wide variance between water transport rates in the xylem of tree species of varying water use efficiency, e.g. English Oak can transport at maximum rates of 43.6m/hr and Beech at 4.2m/hr., *Kramer & Kozlowski, (1979), Table 13.3.*

2.61.2 ***Internal Competition for Water***

Although younger leaves are the first tissues to wilt they are usually the last to die, *Kramer & Kozlowski, (1979) page 478.* This is in accord with the general concept that younger plant parts obtain water at the expense of older parts.

2.61.3 ***The Impact of Pruning***

The effect of reduction of crown area varying from a control to 90% reduction on height growth in 5 years is small, i.e. difference in height between the control and 90% leaf tissue reduction is only 3m; *Kramer & Kozlowski, (1979), Figure 17.17.*

Poorter & Lambers, (1991) considered that it was not the proportion of biomass invested in leaves (LWR) that determines relative growth rate (RGR) but rather the amount of leaf area per unit plant weight (leaf area ratio, LAR). Thus large leaves of low weight are more efficient than smaller thicker leaves. This is what might be found with the leaves of trees produced after being pollarded.

Findlay, C et al (1997) showed that pruning of apical shoots resulted in a 300% increase in shoot growth compared to trees which only had lateral shoots pruned.

2.0 Review of Available Literature (Continued)

2.63 Summary of literature search

What quickly becomes apparent from the above literature search is that the complex feedback loops that help create the cybernetic system of plant, fungal, soil, air and water continuum we like to think of as a tree system have been ignored by arboriculturists, if not other researchers. The obvious conclusion is that we have not created a common Model Urban Tree and that in not doing so we have invariably extrapolated shallow results, conclusions, conjectures, hypothesis and pure untruths across whole tree populations, ignoring the key physiological, biological, genetic and investigative results which are widely available.

3.0 The Model Tree

3.1 In an effort to understand the interaction of trees and soils that can result in subsidence events in low rise buildings, it is proposed that a framework or model of how this might occur would be of assistance. Such a generic model could be modified as research becomes available and our understanding increases. Therefore, a basic description of how trees grow and how their roots systems function is presented below.

3.2 From the literature review presented in Chapter 2, it is obvious that there is a large volume of research on the subject of tree roots and the rhizosphere in general. However, there is very little in the published literature about tree roots in relation to the area beneath modern house foundations.

3.3 It has been established that roots and especially tree roots have a major benefit in terms of slope and soil stabilisation. This is particularly important for recommendations associated with subsidence events in proximity to railway and other man made cuttings / slopes. Tree removal may well serve to limit transpirational loss whilst predisposing the slope to slip or creep as tree root biomass is reduced within the slope soil environment.

3.4 The importance of healthy soils and trees for continuity of a fine root population is obvious. The data certainly indicate that tree roots can be beneficial in terms of soil and slope stabilisation. This effect seems to be directly related to the extent and distribution of the root hairs and non-woody roots which seem to be the most important element in the root / soil bond.

3.5 The effects of root exudates is a very complex subject and not well understood at the present time. However, it would seem that roots do affect the weathering of soil in the rhizosphere.

3.6 There are many methods available for root investigation and the UK seems to have a good base for this work.

3.7 *Ward, (1947)* asks questions which are still pertinent today and remain unanswered. All the available information suggests a need for detailed investigation of a site and arboricultural assessment of the trees. There is a large volume of data becoming available on fine root growth, which indicates the role that it plays in tree nutrient cycling. The use of computer models to simulate root growth may provide a useful research tool for designing and interpretation of experiments in the field.

3.0 The Model Tree (Continued)

3.8 An overriding requirement for good root growth is soil bulk density and the size and connection of pore spaces; however, oxygen availability could be the most critical factor in limiting soil exploration, particularly on clay soils. Increased soil temperatures do have an impact; however, some plants seem to be able to cope with / adapt to the changes in water potential. Restriction of root growth by chemical manipulation of the soil may be a possibility; American research with bio-barriers looks promising.

3.9 The paper on climate change does not seem to take into account the ability of vegetation to adapt to changes in the environment. There are several papers which show how flexible / adaptable trees are in their ability to control rates of water loss. However, there seems to be a measure of agreement on the fact that these responses may only work in the short term, i.e. for one generation. It does not seem that the impact of climate change on vegetation will be immediate, but the next generation after climate change will struggle not only with physiological requirements but also with competition from other plant species, pests and diseases.

3.10 Roots are involved in creating soil structure and drainage channels. In the latter case they probably increase their exploitation of the soil via existing cracks or cracks developed by their own action in wetting and drying of the soil. This explains how they are able to extend their resource uptake area in clay soils whose bulk density and pore size / distribution would normally be inhospitable to root growth. The most important limiting feature for root growth seems to be the availability of air. This is measured through soil bulk density and the size of the connecting pore spaces. Increased soil temperature does impact root growth, but most tree species seem to be able to adapt to this and alterations in available water.

3.11 The fact that competition does restrict growth is clear; however, the problem of using this to manage vegetation requires a clear understanding of how the response strategy used by the plants could be controlled.

3.12 The MORECS data produced by and available from the Meteorological Office is among the most useful direct information. This provides detailed temporal and spatial data upon the water deficits in the soils throughout Britain. The trends available from this database, particularly as it relates to the upper 1000mm, where most susceptible low rise building foundations are likely to be located, could prove extremely useful.

3.0 The Model Tree (Continued)

3.13 Some of the computer models available for simulating root growth could be beneficial in design and or interpretation of field experiments. There are a number of useful techniques available for studying root growth in the field. It looks likely that there is a suitable methodology available to suit most data gathering purposes. The use of rhizotrons in set experiments could be considered.

3.14 Control of tree growth by chemical, physical and biological means is possible. The practicality of these methods in the field would be dependent upon a number of variables, as follows:

> Physical treatment of the soil to alter bulk density;
>
> The use of artificial root barriers could be considered in some situations;
>
> The use of chemical and or biological methods carry with them adverse side effects such as soil pollution, ecology and conservation issues. However, some newer geotextile membranes are now impregnated with root inhibiting chemicals, which are environmentally neutral.

3.15 A most significant observation is that trees can adapt their water use and rooting pattern to accommodate environmental changes. They can do this in relatively short time periods. This may not be so of younger plants in the future, when after climate change, the next generation of trees may struggle to meet their physiological requirements with competition from other plants.

3.16 Traditional management techniques to control tree water use are based on linear models of soil, plant, atmosphere interactions and cannot be supported by the literature.

3.17 ***How a Tree Works - Established First Principles***

3.17.1 In simplistic terms, a tree is comprised of three parts, **(i)** roots; **(ii)** trunk and **(iii)** crown. All three are inter-dependent and are linked by a series of pumping mechanisms. In all respects, the tree is dynamic, i.e. it is in continuous motion and changes with time. In addition, it is important to note that trees are generating organisms, i.e. they get bigger as they get older. Unlike an animal system, which has a genetically pre-determined maximum size within certain limits, by contrast, trees continue to grow within the limits of vigour and generate new parts in new places to replace damaged parts. Trees cannot repair or regenerate damaged parts.

3.0 The Model Tree (Continued)

3.17.2 The **roots** of trees have three primary functions, absorption, support and storage. The root system comprises two parts; *woody roots*, the functions of which are support or anchorage and storage of starch reserves; and *non-woody roots*, often loosely called feeder roots absorbing water and mineral nutrients from the soil. These also form associations with fungi called **Mycorrhizae**, (***Mycor*** meaning Fungus and ***Rhiza*** meaning Root). This association is often vital to tree establishment and persists in many species throughout the life of the tree. The mycorrhizae assist in the fixation of essential nutrients and in turn derive carbohydrate from the tree. They can be internal, **Endomycorrhizae** or external, **Ectomycorrhizae**.

3.17.3 The **trunk**, sometimes called the bole or stem, is comprised mainly of wood and is the main support for the crown and the link between roots and shoots. It contains tissues, the function of which is to transport water, (xylem) and associated tissue, and tissue relating to the transport of carbohydrate, (phloem). Water is transported from the roots to the shoots, while carbohydrate is transported from the shoots to scaffold branches and the roots. The trunk also stores carbohydrate in the form of starch.

The diagram at **Fig 3** illustrates the model tree.

Fig 3

3.0 The Model Tree (Continued)

3.17.4 The **crown** of the tree contains the main scaffold branches, smaller branches and twigs or shoots. All portions may contain leaves and these are the structures which are predominantly involved in photosynthesis, i.e. making carbohydrate by combining energy from sunlight with water and carbon dioxide. Water is supplied from the roots while the carbon dioxide is absorbed from the air.

3.17.5 A tree, conifer or broadleaf, evergreen or deciduous, is a system of dynamic pumps; trees are in effect complex biomechanical pumps and they form a continuum between the clay soil and atmosphere. Interfere with the system at any stage and dysfunction occurs. Trees can cope with dysfunction for periods of time but continuous and applied pressure can cause stress and strain leading to decline and death.

3.17.6 The nature of the root system is often misunderstood. It is often held that the roots reflect the trunk and occupy a similar space below ground as the crown does above ground and mirrors it. In fact, the root system of a tree may be very shallow and often comprises long, relatively small, lateral roots, spreading out close to the soil surface, rather than a deeply penetrating tap root. It is uncommon for trees growing on clay soils to have rooting systems deeper than 2 metres although fine roots can extend to 10m or more in exceptional circumstances and particularly in urban areas with complex soil and man-made structure relationships.

3.17.7 The deepest roots are often found directly below the trunk or close to it. Maximum depth varies greatly from 100-200mm in waterlogged, compacted or peaty soils, to many metres in loose, well aerated soils or fissured rock. Analyses undertaken by the Royal Botanic Gardens at Kew following the storm of 1987 indicated that 44% of all roots were in the first 1000mm while 95% were located in the first 2000mm; *Cutler, et. al. (1990).*

3.17.8 It must also be remembered that root growth is opportunistic, occurring only where the soil environment can sustain it. Roots proliferate where they encounter favourable conditions of air and water and in this regard the area beneath man-made structures can provide ideal conditions for root proliferation. Tree roots work on gradient systems moving from areas of resource depletion to new Resource Depletion Zones, (RDZs). Trees effectively manage resources within the root zone by depletion and recycling strategies and move across gradients from areas of low concentration of a given resource to areas of high concentration.

3.0 The Model Tree (Continued)

3.18 *Tree Stability*

3.18.1 While the importance of tree roots for increasing the shear strength of soils has been shown, it is also important to consider that tree stability is also critical, especially on slopes which adjoin transport corridors such as railways or motorways, for two reasons:

3.18.2 *Increased Erosion & Safety*

3.18.2.1 The wind throw of trees with their root systems causes extensive soil structure disruption and exposure. On slopes the weight of the fallen tree may be sufficient to cause other trees up slope or down slope to be more vulnerable to further storm winds or under-cutting of root systems.

3.18.2.2 Falling trees may be a direct danger to people or property adjacent to the embankment or slope. The implications of the above for root barriers, trench construction for underpinning schemes, new drainage, removal of trees near to slope edges and wind firm on other trees down slope should not be underestimated. The stability of trees has been the subject of detailed research in this country the United States and Germany.

3.18.2.3 Following the storms of October 1987, a survey of wind blown trees, *Cutler et al. (1990)* found that, with exception of a few species, e.g. Spruce (*Picea* spp.), which had very large surface roots, all root diameters decreased rapidly away from the base of the tree, with few roots being greater than 50mm at 1.50m.

3.18.2.4 The work by *Coutts, et al. (1995)* shows the importance of wind exposure to root development. Trees that are wind stressed have a 60% increase in larger roots on the windward side of the tree compared to roots growing at right angles to the direction of the wind. Some 55% of the stability of the tree is derived from the tension anchors provided by the roots on the windward side of the tree root plate. In wind tunnel experiments it was found that there is a general increase in the numbers of fine roots (less than 2mm diameter), on the windward and leeward directions. This is essential because the fine roots provide the high surface area contact with the soil, which provides up to 30% of the stability of trees.

3.0 The Model Tree (Continued)

3.18.2.5 *Mattheck et al (1994),* shows that the radius of the root plate required for stability is related to stem radius. Thus the larger the tree the greater the forces being transferred to the soil via the root system. Mattheck also shows that root plate radius is proportionally greater for trees with a stem radius below 300mm. This is due to the fact that as the tree increases in size its weight above ground starts to have greater impact on stability. That is, the weight of the tree acting down on the soil increases the shear resistance at the root system soil interface. In regard to trees on slopes with underlying strata that restricts rooting depth this is an important consideration. This is because as the tree increases in height and weight the gravitation forces down the slope require increased root growth. If this does not occur then the risk of windthrow is increased.

3.19 *Root Plate Development*

3.19.1 Shallow soil may be regarded as inhibiting to root development through compacted layers, bedrock or poor drainage, to the depth to which the tree roots can develop a permanent "system". For example, roots may not be able to survive all the year round in soils with high water tables or in clay soils at saturation.

3.19.2 In such "shallow" soils, because the depth of rooting is not possible all year round, there is a reduction of soil volume. Thus one of the "stability factors" that allows the tree to stay upright is compromised. It has been reported that to make up this deficit the adaptive growth response is to increase the general diameter of the root mass, on the windward and leeward sides, to improve the "rigidity" of the soil-root plate, thus increasing the bending moment at which failure would occur and hence counteracting the increasing vulnerability to wind throw as the tree grows; *Bruce, et al. (1996).*

3.19.3 Given the above it is obvious that great care should be taken with any excavations that occur in relation to trees on shallow soils, i.e. even a small reduction in the width of the "rigid root plate" of a tree on shallow soil will have greater impact on stability than a similar loss to that of a tree on a deeper soil; *Wessolly, (1996).*

3.0 The Model Tree (Continued)

3.20 *Wind Throw*

3.20.1 Wind throw is the failure of the whole tree including a proportion of the roots and the adhering soil. Damage by wind throw causes important economic losses to forestry in the UK and a number of fatalities each year in urban areas. A common feature of unstable trees on wind exposed sites is shallow rooting caused by unfavourable soil conditions at depth. Attempts to reduce wind throw in forestry usually involve treatment of the site e.g. drainage and deep soil ripping. It is common that on many clay soil sites in the UK that development and building construction activity create compacted soil conditions, impeded drainage and subsequent rooting in the upper horizons by trees.

3.20.2 Manipulation of the trees themselves by selection of those trees with good root systems is still in its early stages. However, it is known that allocation of resources by the tree between root and shoot growth is critical, i.e. trees that allocate too much of their resources to shoot growth tend to be more unstable.

3.21 *Relationship Between Crown Size and Stem Diameter and Wind Throw*

3.21.1 The relationship between tree crown size and stem diameter and wind throw has been investigated by *Wessolly, (1996),* which indicates that trees of the same stem diameter can have a crown areas that vary by a factor of 5. In addition *Wessolly (1996)* states that the loading on the stem may range by up to 800% in trees of the same diameter.

3.21.2 The management of all trees requires consideration of the value for various amenity functions and the risk that they may pose to people or property. On sloping sites there will be the need to consider the impact of tree loss on stability of the slope, particularly where tree removal is required as a result of damage to nearby structures, which might subsequently be damaged further by slope creep. Reduced shear strength due to root death or exposure of bare soil may give rise to erosion or more serious landslide events, which in themselves may result in major property damage, injury and / or death.

3.0 The Model Tree (Continued)

3.22 *Towards a Working Model*

3.22.1 A model of how a mature tree might function in relation to a building with 1000mm foundations is presented as a set of transparent overlays at **Appendix 2**. This is a composite overlay transparency in which all the relevant aspects are drawn together and illustrated. It is stated here that not all aspects occur with all trees in all situations, rather this is an empirical model in which all eventualities are considered.

3.22.2 Essentially, the model describes, in a visual format, the problems trees may cause for low rise buildings. Given the complexity of the tree as a system, management of trees in the context of subsidence damage to low rise buildings requires much more data before coherent decisions can be taken. Currently decision making is based on little knowledge.

3.23 *The Clay Soils, Vegetation and Climate Continuum*

3.23.1 Whilst there are undoubtedly some excellent reference works associated with the above components of the problems associated with building failure there is not at present any fully integrated model of how all these processes interact. This section of the Dissertation is supplemented by a discussion and description of the dynamic processes that are involved as water leaves a clay soil. This model is the preliminary product of my collaborative work with Mr Michael Crilly, a Geo-technical Officer with The Building Research Establishment.

3.23.2 It has been established that annual precipitation over the UK is normally more than adequate to replace the summer evaporative loss from soils. Additionally the unique properties of clay have been widely discussed and illustrated to indicate how these soils are constituted chemically, how the clay mineralogy encourages water to bond with the clay particles and the various effects of cohesive and capillary forces within the clay matrix. The discussion of the physiological processes involved during transpirational loss indicate the main pathways for water loss in trees and how the key process of mass flow of water affects the internal condition of the tree's biology. The working model for these processes is now offered as a clay, soil water, plant - atmosphere continuum.

3.0 The Model Tree (Continued)

3.23.3 The clay soils of the UK whilst differing markedly in terms of their chemical composition, maintain the common function of attracting water and bonding this water to their surfaces against the normal gravitational gradient. This water bonding reaches a maximum level and the envelope of bound water is then fully saturated. Suctions within the soil at this point will be naturally low and additional free water will often be present within the larger capillaries formed as a matrix within the clay soil. This seasonal "tidal" movement of water is initially and primarily associated with the agricultural and "agri – engineering" boundary soils. However the addition of vegetation to the equation facilitates the effective transport of water from the clay soil and to the atmosphere, the tree is simply a very effective highway for water to move as a "mass flow" from soil to air during transpiration.

3.23.4 The possibilities of trees influencing soils with a known plasticity will be linked to '**Soil Moisture Deficits**', (SMD), that occur seasonally as evapo-transpiration exceeds precipitation in summer months. During the winter, the clay, if permeable, will re-hydrate; *Ross, P.J. and Bridge, B.J.(1987).*

3.23.5 Trees represent the single most important factor in relation to water loss from clay soils. Trees actively transpire water by absorbing soil water and transporting this water to leaves, where it is lost to the atmosphere through stomata. Water is also evaporated from leaves, branches and stems by sunlight and the atmosphere and this "umbrella effect" prevents precipitation, which falls on plant parts from reaching the soil; *Lawson, M. (1995.)*

3.23.6 Comparisons of SMD beneath various land use types taken with the research results reviewed in Chapter 2, suggest an effective starting point for a model of water use and loss on cohesive soils, as follows:

- Woody tree roots are perennial and generally maximise resource (water) utilisation in a structured manner.
- Trees can rapidly deplete the upper horizons of available soil water.
- The volume change opens up fissures in the clay soil which the tree further exploits.
- During the summer trees can abstract water from soil at a rate, which exceeds that at which water from rainfall can recharge the soil.
- The above occurs as a result of transpirational loss and because tree canopies form effective umbrellas allowing evaporative surface area to be high.
- Trees can lose water throughout the summer and long into the autumn.

4.0. Managing Trees Implicated in Subsidence Damage to Low Rise Buildings

4.1 It has been suggested previously that a very high proportion of the structural damage associated with subsidence of low rise buildings is the result of tree related soil drying. The affect of this loss has significantly influenced the management of urban trees in the UK and many millions of pounds have been expended attempting to control the water use of trees through removal or pruning. The pruning regimes have further complicated any cost -v- benefit analysis of the issues and many thousands of trees have been subjected to traumatic tissue loss leading to "short life" due to the impact of over pruning on biological functions.

4.2 The management of subsidence events and/or risk by tree pruning has a history that certainly dates back to the 1920s & 1930s. However the type of over pruning, often loosely termed "pollarding" in which large forest type trees have all scaffold branches removed, was undertaken as part of maintenance programmes, because managers of urban trees relied on "folk wisdom" and countryside techniques associated with small wood production for firewood. It is doubtful that city managers, homeowners, landowners or the professional/financial community gave the problem of minor cracks in roads and buildings or refurbishment of these structures, much consideration prior to the explosion in insurance services in the 1970s; *Lawson, (1996).*

4.3 The engineering community was certainly aware that clay soils could shrink and swell and has been for decades. Guidance on foundation depths of buildings has been produced since the 1940s. However only as the financial community began to suffer during the early 1970s was the problem investigated in any detail. Since that time, a debate has developed associated with the various remedies that exist in relation to subsidence of low rise buildings. Certainly the favoured arboricultural remedy to the problem of managing water loss from trees on shrinkable clay soils has been heavy crown reduction. I have questioned the effectiveness and thus the value of this remedy throughout the 1990s.

4.0. Managing Trees Implicated in Subsidence Damage to Low Rise Buildings (Continued)

The various remedies are characterised as follows:

Remedy	Issues
Underpinning & Other Engineered Remedies	Seeks to put the foundation depth to below the depth of the influence of soil water abstraction by vegetation. The most expensive option with fees ranging from £10,000 for a simple underpinning of bay windows to £500,000 for complex underpinning of large properties.
Root Barriers	Seeks to isolate the vegetation from the property, by 3 - 5m trench and then a barrier, now usually an impermeable geotextile membrane inserted into the trench. Limited use on properties, which are anything other than detached and difficult in most urban gardens. Prices in the range £10,000 - £20,000 for an effective barrier.
Withdrawal of Insurance Cover	An agreement to allow for removal of subsidence cover in the event that the insured does not wish to fell the tree(s) in question, between the insurer and insured. Can blight future sale of property and can lead to diminution in land values.
Cosmetic Superstructure Repairs	Acknowledges that future movements are likely in the absence of tree management. Relatively inexpensive to insurers. Potentially costly to owners who cannot sell their home.
Tree Pruning	Seeks to limit tree water use by removal of leaf surface area such as to reduce amplitudes of movements of structures. Relatively inexpensive, however does require extended period of monitoring to ensure remedy effective, thus leading to higher management costs to insurers. Damaging to amenity and longevity of tree species.
Tree Felling	Seeks to remove the impact of vegetation on soil water and to hence stabilise foundation movements. Relatively inexpensive but can lead to damaging heave type movements.

4.0. Managing Trees Implicated in Subsidence Damage to Low Rise Buildings (Continued)

4.4 Throughout the 1980s and 1990s the utilisation of underpinning grew rapidly and peaked in the early 1990s. Thereafter as the cost to insurers increased to over £500 million each year for subsidence claims; *Association of British Insurers, (1990/1991),* alternative remedies were pursued. This has been the driving reason behind the growth of Arboricultural consulting services since 1990. Insurers can no longer afford long claims periods combined with expensive solution of underpinning in an effort to halt or limit further ground related movements. It is clear that whilst underpinning and structural reinforcement, such as the corset type "Hoopsafe" system will continue to play a role in subsidence cases, vegetation management is the focus as the main remedy.

4.5 As already discussed, although root barriers with chemical or other controls can be utilised, the site specific requirements for ample working area and no third party requirements for excavation have combined to limit the use of root barriers within the management matrix.

4.6 Equally, the nature of property and land values makes superstructure repairs and removal of subsidence cover extremely unattractive to insurers and the insured alike.

4.7 If we anticipate continued periods of dry weather and an increase in the annual number of claims in the tens of thousands, we must, as Arboriculturists, expect and respect the fact that vegetation management will continue to play the main role in controlling movements associated with soil volume change and damage to low rise buildings.

4.8 ***Tree Pruning***

4.8.1 It is clear that the trees in urban areas have been pruned for a variety of reasons throughout this century, *Lawson (1995).* The use of "tree surgery", the development of modern light chainsaws and the slowly developing nature of our understanding of tree biology have all led to adoption of tree pruning as a sensible way to maintain forest type trees in urban areas as the response to problems that trees cause by judicious tree work.

4.0. Managing Trees Implicated in Subsidence Damage to Low Rise Buildings (Continued)

4.8.2 The relatively recent development of an Arboricultural industry, with tree work specialists, consultants and local authority officers dates from the 1960s. What could therefore be more natural than to look at the management of tree water use by way of the removal of the water "leaking" tissue?

4.8.3 The scientific review of technical papers as part of this dissertation casts great doubt on any linear model for tree water use and equally for the likely success of any strategy for the removal of tissue as a way to control water use.

4.8.4 There is little new in this assertion and it is interesting that the British Standards Institute *"Recommendations for Tree Work"*, ***BS3998: 1989***, supported by the Arboricultural industry frowns on the heavy reduction of forest type trees at maturity. In fact the main supporter of pruning as a method of control of tree water use, P.G Biddle, states within his Arboricultural Advisory Information advice note 108/92 EXT:

"If the movements are entirely seasonal, it may be possible to reduce the amplitude of this movement to an acceptable level by pruning the tree so as to remove leaf area … greatest benefits will be achieved if the building is near the outer limits of influence, pruning a large tree which is only a few metres from the building will probably have little benefit … if there is a significant persistent deficit, pruning alone will not be effective"

The model that I have developed with my co-workers over the last decade suggests:

The early life and juvenile stage of the model tree's development is dominated by high leaf to root ratios. At this stage the tree is Shigo's "Tree 1" of the 3-Tree Concept; *Shigo, (1992),* being more leaf than stem and woody root. Invasion of the soil environment is at this stage limited. As the tree matures its leaf size reflects the growing impact of soil moisture deficits and the developing need for a major investment in root growth to satisfy the tree's daily water use. Leaf size diminishes and / or the tree begins to utilise a shade / sun leaf strategy, with drought tolerant sun leaves dominating the canopy fringe and shade leaves with lower drought tolerance within the layered canopy.

4.0. Managing Trees Implicated in Subsidence Damage to Low Rise Buildings (Continued)

4.8.5 It has been my contention for a considerable time that pruning is unlikely to impact tree water loss in any linear way. Rather the tree's response to tissue loss will be dynamic and currently inherently unpredictable. We do know that topping mature trees leads to high respiration rates and when stored energy is available to the production of many new leaves in new spatial positions. This new tissue production often shows rapid elongation rates with larger leaves, increasing stomatal area and allowing the new canopy to be serviced by an initially stable root surface area.

4.8.6 This contention is now supported by work developed by the Building Research Establishment (BRE) and by the technical review set out in **Chapter 2**.

Attached as **Appendix 3** are the research findings for an 8 year study into the impact of tree topping on London Plane at the Queens Park Estate, central London.

4.8.7 The Queens Park Estate consists of late Victorian two storey terraced houses. The surrounding footpaths are narrow and at the time of or shortly after construction, London Plane trees (*Platanus acerifolia*) were planted at 20m spacings and maintained through their early life as true pollards. During the 1960s/1970s the pollard strategy was stopped and the trees responded by extending branches and roots. The properties were council owned until the late 1980s and the occurrence of cracking to frontages was not reported. The explosion in property ownership, the housing price boom and changes in the circumstances of the residents of Queens Park led to reported subsidence events coinciding with the severe drought period of 1988 - 1992.

4.8.9 The BRE were commissioned to begin a programme of verticality level monitoring of a large number of properties at the same time as the Council reverted to a topping / pollard strategy to previous pollard heads for all trees and on a two year topping trim cycle.

4.8.10 The results of the monitoring indicated at [**Fig 4**] illustrates a sample from the research programme with monitoring points at distances from the trees of between 2 and 10 metres. The verticality measurements are extremely sensitive to movements of only 10^{ths} of 1mm and in this sense, rather than any measurement of crack widths complicated by building dynamics, accurately assess the changes in the plastic profile of the soil surrounding the target structures.

Fig 4

4.0. Managing Trees Implicated in Subsidence Damage to Low Rise Buildings (Continued)

4.8.11 It is clear that following topping in late 1992 the total verticality movements ceased almost completely during 1993. This could almost be considered a successful result indicating that reduction in leaf area can limit water loss. However during subsequent years the trees seem to increase water loss at rapid rates culminating in 1996 with extremely high levels of vertical movement, which would result in structural movements completely unacceptable by modern standards. There then seems to be a period of relatively settled water use culminating in the latest results during late summer 1999. Can the above be explained by the proposed model?

4.8.12 The initial topping event came for the trees after a long period of uninterrupted growth and likely expansion of the rooting environment. The model anticipates that throughout this period trees would have "gradient chased" water resources beneath the Victorian properties. Total root biomass is expected to have been high at the time of topping of the Plane trees.

4.8.13 The immediate reaction of the tree to this change in leaf surface area obviously produced a first season "shock" at the change in status of the root / shoot ratio and water use was effectively curtailed. Following on from this first year one might anticipate a major reallocation of resources to shoot production as the tree sought to manage dynamic equilibrium. Thereafter the trees overcompensate for the damage done to the leaf area and this culminates with the water loss and verticality maximum figures, not in the drought year 1995, but rather to the plants own timetable in 1996.

4.8.14 The principle of cybernetic systems and particularly biological systems overcompensating for such changes to their "natural state equilibrium" has been well known by the scientific community for almost 100 years; *Wiener, (1950)*. Following on from the managed process towards a new equilibrium the trees eventually find an annualised maximum water requirement, which whilst it might grow over time is adequate for the plant's current needs.

4.8.15 It is crucial to note that the impact on the tree's ability to lose water at significant levels lasted for a very short time and that the plants response was dynamic and consistent with an attempt to create an equilibrium of water use as postulated in the Model. The model is shown to be robust in anticipating the responses of plants to attempted linear management by Arboriculturists.

4.0. Managing Trees Implicated in Subsidence Damage to Low Rise Buildings (Continued)

4.8.16 The actual canopy height of trees can be considered for control in a variety of other ways, as follows

(i) Species selection

(ii) Tree growth regulators, (TGRs)

(iii) Partial ring barking

4.8.16 (i) Species which grow to a limited size will clearly be beneficial, e.g. Rowan. However, with an existing vegetation cover, changing the species on any particular site is a long-term solution. This is because felling and replanting may result in adverse amenity impacts before the new plantings are sufficiently established and as a result of the change of scale from forest type trees to smaller ornamentals.

4.8.16 (ii) The development of tree growth regulators, particularly in the United States has resulted in a situation were it is possible to limit tree growth by use of a chemical soil drench. However, these products are not yet cleared for commercial use in this country and its use in urban areas could be problematic, i.e. run off and effective control. In addition they could not be used to reduce the existing canopy height.

4.8.16 (iii) If one were to consider any other form of above ground tree tissue control then an alternative method to pruning management might model the issues rather differently.

4.8.17 Root growth in woody plants, environmental and physiological factors being equal, is primarily dependent on photosynthetic products transported from the leaf via the phloem, e.g. woody roots do not generally have the means of producing their own sugars required for cell metabolic activity and growth. The factors affecting photosynthetic transport via the phloem are:

- Photosynthetic efficiency
- Efficient transport route
- Sufficient sink strength

Given that each of these can be manipulated, to a greater or lesser degree, to effect transport rates, consideration of the implications of manipulation and its effects on root growth can be discussed.

4.0. Managing Trees Implicated in Subsidence Damage to Low Rise Buildings (Continued)

4.8.17.1 ***Photosynthetic Efficiency***

4.8.17.1.1 One way of affecting photosynthetic efficiency is by manipulation of leaf area. Leaf area can be reduced by pruning or chemical treatment to achieve a percentage of leaf area reduction. As stated above it has generally been shown that to have any significant effect on growth, leaf area reductions by pruning needs to be in excess of 60 - 90%. The consequences of such a reduction depends on species and tree physiological status, but again all things being equal, the response of the tree will generally be that of replacing the removed leaf area as soon as possible or entering a spiral of decline.

This results in impacts on root growth, efficiency of new leaves and transportation of sugars. The impact on roots is to limit any new growth and possibly reduction in the root hair (7 to 15 microns in dia.) density, however, it would not reduce the extent and density of any of the main roots system and minimal loss of fine roots (2mm down to 50 microns in diameter). New leaves that emerge following pruning to the above levels are different in their structure and morphology, which affects photosynthetic output. This is because they are generally larger and thinner in size, they are not shaded by other leaves and because there are limited numbers, (compared to the pre-pruning situation), there is limited competition for water (the extent of root system not initially being affected) and essential elements for photosynthesis are freely available. Thus it is generally found that the plant can soon have a photosynthetic output similar to that before the pruning. In addition, because of the high growth rates, the photosynthetic transport is not inhibited at the leaf by the presence of previously manufactured sugars.

4.8.17.2 ***Efficient Transport Route***

4.8.17.2.1 The phloem is generally an efficient transport route with rates sufficient to deliver sugars to actively growing plant parts. The main route of transport is along the axial direction of phloem vessels. However, there is a certain amount of lateral transport, but this is of a much lower rate than the axial route. Manipulation of the phloem transport route is an old method used in fruit tree production, prior to the advent of dwarf root stocks, to check root growth and hence vegetative growth and bring on fruit production. Thus by restricting phloem transport it is possible to limit shoot and root growth.

4.0. Managing Trees Implicated in Subsidence Damage to Low Rise Buildings (Continued)

4.8.17.3 ***Sufficient Sink Strength***

4.8.17.3.1 As discussed if there is insufficient rates of transport out of the leaf, due to a build up in previously produced sugars and or limited growth, then photosynthesis will be limited. Manipulation of sink strengths by pruning will limit root growth for a period but as discussed this is quickly reversed following new leaf growth. However, limiting transport of the phloem system will limit root growth both by inhibition of photosynthesis and the rate at which sugars reach the root system.

4.8.17.3.2 The impact of this can be best understood by the fact that between 30% and 60% of the tree's photosynthetic output goes to the root system. If the root system's energy requirement cannot be sustained, then it will not be able to maintain the extent of its resource area for mineral elements and water uptake, e.g. reducing transport to roots has a far greater impact on whole tree growth than reducing phloem transport to any other part of the tree.

4.18 ***Methodologies for Restricting Phloem Transport***

4.18.1 In fruit tree production, prior to dwarfing root stocks, three cultural methods were used:

(i) Grassing the area under the trees.

(ii) Physical force, using a large wooden stave or iron bar, applied to the trunk of the tree.

(iii) Cutting of a narrow strip of bark and phloem out of the trunk or branch.

4.18.2 The first method provided competition, mainly for water but also to some extent for nitrogen. In forest type trees and in urban areas this method would lead to increased competition and potentially deeper rooting of trees and is to be avoided

4.18.3 The second method caused physical damage to the phloem vessel by the force applied to the bark; this may sound unlikely but it has been shown that even small forces applied to the bark are sufficient to cause disruption of the phloem.

4.0. Managing Trees Implicated in Subsidence Damage to Low Rise Buildings (Continued)

4.18.4 The final method, generally known as "ring barking" was a highly specialised practice. In fact it did not mean taking out a ring of bark but two half circles of bark separated by a defined distance depending on the diameter of the stem, (**Fig 5**). The width of the strip of bark removed was usually less than 12mm. This operation disrupted the phloem transport but allowed lateral transport in the gap between the two rings of removed bark and the narrow width of the strip reduced the risk infection and meant that the wound closed up within 5 to 6 years. Thus the operation needed to be repeated in a similar time frame.

The logistical modeling of the technique has been undertaken in collaboration between O'Callaghan Associates Limited and Chartered Loss Adjusters, Cunningham Ellis & Buckle. Several test sites have demonstrated the applicability of the technique as a low cost pruning technique. More formal field-testing is in progress at this time and results cannot be included in this Dissertation.

4.19 ***Tree Felling***

4.19.1 Tree felling is viewed by many landscape professionals and the public as the worst case scenario in relation to management of subsidence of low rise buildings. However, there can be no doubt that removal of vegetation effectively stops the loss of water from clay and allows the soils to restore the equilibrium of moisture content. Following recovery, damaged structures can be repaired and land / buildings will maintain their value free from the "blight" of a subsidence event.

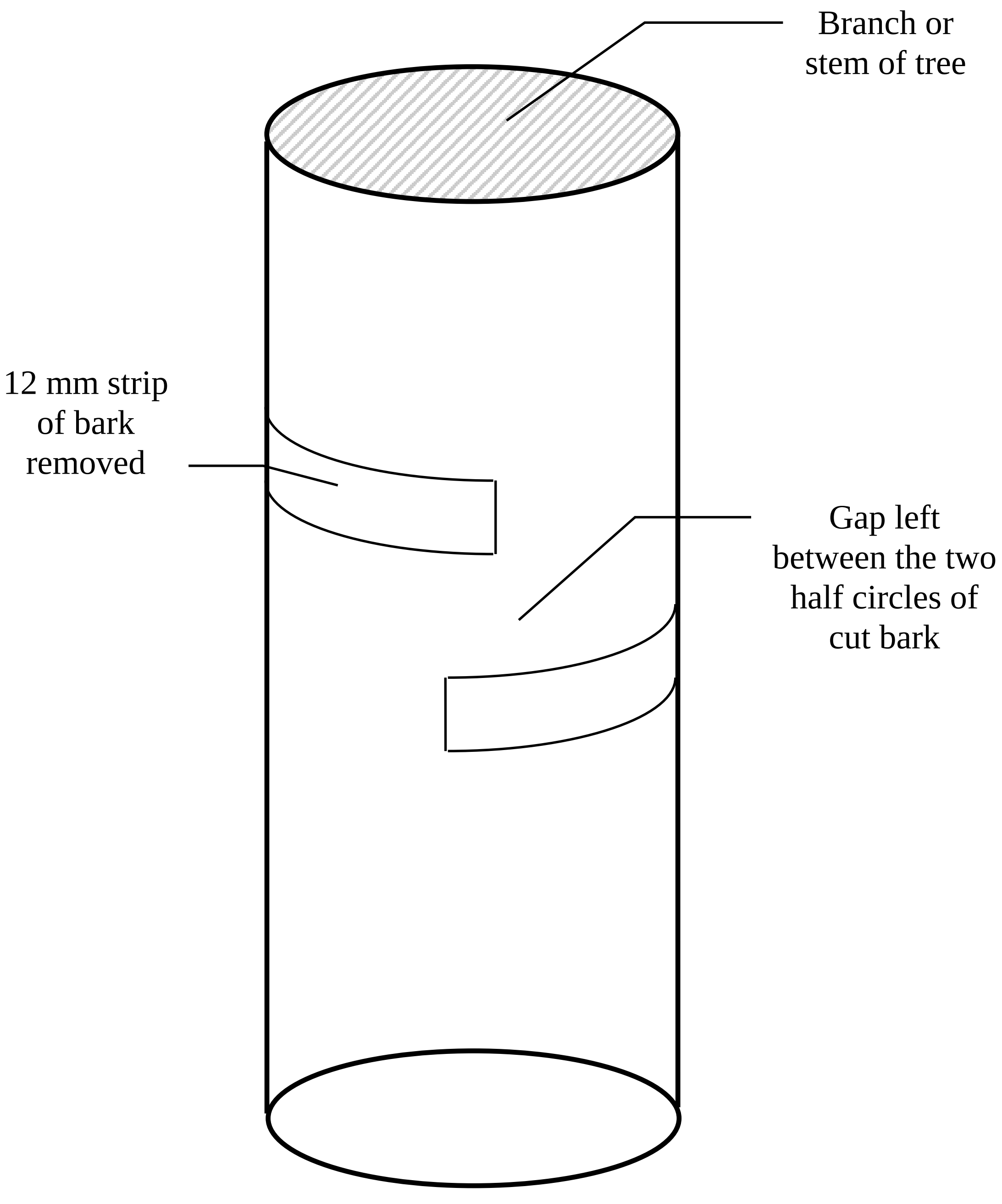
4.19.2 It is interesting that the Arboricultural and landscape community vigorously resist the removal of trees associated with subsidence damage to low rise buildings. However, Arboriculturists have for many years respected tree loss associated with:

- land clearance for new development
- improvements to infrastructure
- reductions in risk exposure from hazard trees
- diversification of landscape quality
- inappropriately planted specimens

4.19.3 There is certainly a fear that tree removal associated with the relatively minor cosmetic and structural damage to low rise buildings sets an unwanted precedent putting people and property before landscape character. The crucial issue is simply this:

Fig 5

Sketch diagram of methodology



4.0. Managing Trees Implicated in Subsidence Damage to Low Rise Buildings (Continued)

The effect of structural damage on a mortgaged property as a claim on an insurance policy, required as part of a mortgage agreement, is to ***"blight"*** the property in an open market when measured against a comparable dwelling. The property suffers ***"diminution"*** in value which may lead to a negative equity in mortgage terms or to an unacceptable risk in insurance terms. In either event the impact is on ***equity*** and not on engineering stability.

4.19.4 Tree felling is an efficient cost effective way in which to manage the problem. When allied to a programme of planting replacement trees and for Local Authorities to landscape appraisal, it should be no more damaging to landscape character than any other management technique.

4.19.5 It is my strong belief that subsidence management by selected removal of trees causing measurable damage to low rise buildings has been wrongly perceived as a major threat to the quality of our towns and cities; *Lawson, (1996*). The cited paper is included as a submission scientific paper subject to peer review as part of this dissertation.

4.19.6 If we are to plan for a modern sustainable urban forest then the impact of all activities which impact in a negative way on the quality of urban landscapes must be considered and opportunities seized to plan, promote and pay for landscape planting and planning on a grand scale.

4.19.7 I hope that this Dissertation can serve as a resource for the development of further initiatives designed to ensure that modern urban landscapes complement human economic growth and our continuing development of sustainable cities.

5.0. Conclusions

5.1 There is a great deal of data available within the literature that can help in the formulation of a model tree. Steps have been made over the last 30 years by various researchers to work towards effective models and researchers such as Kramer & Koslowski, Shigo, Mattheck, Cutler & Richardson, McPherson *et al* and Mattheny & Clarke have all generated cogent testable models. However the management of trees causing problems rather than contributing positively to urban sustainability is still something of a "black art". Perhaps it is natural to not wish to be labeled as a "tree hater" by drawing out the very obvious conclusion that trees cause misery to many thousands of the residents of our towns and cities when improperly managed, that millions of pounds are wasted investigating the very obvious links between cause and effect and that often removal is the most prudent answer.

5.2 Regardless of the above a model is now presented for the investigation of the problems caused by trees growing adjacent buildings and on shrinkable clay soils. It is clear that investigations should acknowledge that household insurance is a community good and safety net against the inherent unpredictability of modern life, it's here to stay; that dry periods come and go and that in concert dry weather acting with "leaky water things" will "take their victims as they find them", that diminution in land value is a civil, social and professional wrong and that vegetation management is a sensible way to control the above problems.

5.3 For OCA (UK) Ltd the above is policy and as the Practice Managing Director I can only seek to guide our investigations into the use of felling and replanting strategies, root barrier solutions, chemical treatments, new and visually non-damaging pruning strategies and ongoing research. If the community as a whole, insurers, lenders, professionals, the public, administrative local government, Parliament or the civil Courts wish to change the current paradigm then we will all have to review the situation. For the moment and into the foreseeable future, subsidence will be part of the risks of urban life and one we will have to manage as professional arboriculturists.

Michael Lawson

23 June 2000

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APPENDIX 1

Morecs Extracts

APPENDIX 2

Model

APPENDIX 3

Model
(BRE Pruning Research)