

CONTROLLING WATER USE OF TREES TO ALLEVIATE SUBSIDENCE RISK

Horticulture LINK project 212

Final report – May 2004



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The results and conclusions in this report are based on a series of experiments conducted over a five-year period. The conditions under which the experiments were carried out and the results have been reported with detail and accuracy. However, because of the biological nature of the work, it must be borne in mind that different circumstances and conditions could produce different results. Therefore, care must be taken with the interpretation of the results, especially if they are used as the basis for commercial recommendations.

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EXECUTIVE SUMMARY	

Background

Buildings and the environment in which we live are key elements of our quality of life. Whether trees grow within a private garden or in a roadside pavement, the general public by and large appreciates them. Justifiably, because trees contribute so much to our environment, as well as their visual contribution to our landscape. But trees and buildings in close proximity can lead to problems, whether restricting light or causing damage by root activity. The planting and management of trees close to buildings therefore needs to be planned and undertaken from a sound science base. In a similar way, the planning process (under the auspices of the Office of the Deputy Prime Minister) needs to take account of the potential for conflict to occur and employ innovative design and careful construction. All this will help to avoid such conflict occurring and ensure that trees are maintained and managed in a sustainable manner.

The Highways Agency (HA) has an extensive roadside estate that extends to 30,000 hectares, which supports more than 25 million trees ranging from London plane to wild service trees. The oldest of these are veteran trees and there is a significant population of trees of about 40 years of age. The estate includes an urban element, although much reduced since the transfer of London's trunk roads to Transport for London. Similarly, there are even more trees on non-highway land, including those on private and public property. Many trees are situated close to structures, buildings, road pavements and footways and controlling soil drying by trees is an important potential management tool in these situations.

Trees are an integral and critical part of urban landscapes that provide important aesthetic and environmental contributions that make towns and cities more pleasant, safer and healthier to live in. Trees can give shelter from noise and wind, reduce chemical and particulate air pollution, provide shade and can add value to nearby properties. Trees also benefit urban ecosystems, by sustaining biodiversity. In addition, they reduce storm water run-off and prevent erosion. Removal of city trees will lead to a decline in the quality of urban landscapes and large-scale felling programmes would not be acceptable to the public at large.

Unfortunately, structural damage is associated frequently with the close proximity of trees to low-rise buildings. Trees can extract water from below the foundations causing some particular clay subsoils to shrink, ultimately leading to failure of the foundations and cracks in the superstructure. The cost of repairing the damage caused by the failure of domestic house foundations, due to subsidence, was during the years preceding this project of the order of £300-£400 million annually. Not all of this can be attributed to the presence of tree roots. However, most of the subsidence incidents in the UK are found to occur in areas with clay soils and in these areas, tree roots are claimed to have an effect on subsidence incidents in 73% of cases (Loss Prevention Council, 1995). Hence the potential for saving on remedial costs, by reducing the need for rectification work, may be around £200 million per annum. Currently, no methods exist that reliably predict which trees may cause damage and not all trees near buildings are implicated. Decreasing water uptake by trees may lessen subsidence risk by conserving soil moisture and

reducing clay subsoil shrinkage. Reducing canopy leaf area by pruning may lessen water uptake and cyclical pruning is recommended in a risk limitation strategy for tree root claims developed by the London Tree Officers Association (1995). Tree pruning is perceived as a potentially effective control measure to conserve soil moisture that could prevent excessive removal of trees, but the hypothesis has never been tested on amenity trees in the urban environment.

The aim of this project was to improve the understanding of how isolated amenity trees use water, and to determine whether reduction in canopy leaf area and root-restriction are sustainable ways to control growth and reduce water uptake from soil.

Two different standard arboricultural pruning techniques were used to reduce the crown size of mature trees. The first, 'crown-reduction', reduces crown volume but allows its natural shape to be preserved. This involves an overall reduction of both height and spread by removing the outer portions of all major branches. The second, 'crown-thinning', reduces the number of side lateral branches coming off all of the major branches not affecting the original volume of the crown. In both cases the normal industry standard is to aim to reduce the canopy leaf area by 30% (BS3998: 1989, Lonsdale, 1999). The growth of newly planted amenity trees was controlled by restricting their roots within water permeable geotextile lined pits.

Methods that allowed the measurement of total canopy re-growth following pruning, whole tree transpiration and linking this to prevailing climate conditions and impacts on soil drying were successfully developed and used. Thus, canopy leaf area was measured using a modified hemispherical photographic technique adapted for single trees and shoot extension and individual leaf size were measured directly. Stable carbon and oxygen isotope discriminations were used to provide seasonal estimates of leaf water use and porometry was used to give instantaneous values. An artificial leaf was developed to determine how evaporative demand (factors driving water loss) was modified within the canopy. Whole tree transpiration was determined by quantifying sap flow. Impacts on soil drying by tree roots were measured using a neutron probe.

Mature wild cherry (8 m height) and London plane trees (20 m height) were used as model species for determining the effects of pruning and newly planted Norway maple and lime trees were used to determine the effects of root restriction. Six major experiments were carried out over a period of five years.

Summary of practical implications

- Recommendations on pruning now can be scientifically rather than empirically based as previously.
- Trees recovered their canopy leaf areas to pre-pruning amounts very quickly (1-3 years) following crown-reduction to normal industry standards.
- The re-growth after crown-reduction produced trees with greater leaf area density ($\text{m}^2 \text{ leaf/m}^3$) because they had larger leaves more closely packed together within a smaller crown volume compared to non-pruned trees.
- Crown-thinning reduced the leaf area density, and generally the trees took longer to recover their canopy leaf area than for crown-reduction.
- Total tree water use (transpiration) was reduced by crown-reduction and unaffected by crown-thinning in the year of pruning.

- Crown-reduction reduced soil drying by trees in the year of pruning, but the effects were generally small and disappeared within the following season, unless the reduction was severe, in which case the effects were larger and persisted for up to two years.
- Crown-thinning did not reduce soil drying.
- For newly planted amenity trees, root restriction was found to be a very effective method to control growth.

Summary of science outputs

- The modified hemispherical photographic image technique adapted for single trees use was shown to provide measurements of total canopy leaf area closely related to those determined using an empirical allometric method based on summation of individual branches.
- Crown-reduction increased subsequent shoot extension on cut branches for a minimum of two years. More new (epicormic) vegetative buds were produced particularly at the cut branch ends. The new shoots grew more rapidly and produced larger leaves with higher nitrogen concentrations and greater abilities to assimilate carbon dioxide than non-pruned or crown-thinned trees.
- Measurements of water loss and carbon isotope discrimination of individual leaves from crown-reduced trees indicated that they had a greater capacity to lose water than those from crown-thinned and non-pruned trees, but were less able to respond to evaporative demand outside of the canopy.
- Differences in soil drying caused by crown-reduction and crown-thinning were related to the changes in total leaf area, leaf size and leaf area density. The boundary layer conductance within the canopies of crown-reduced trees was less than for the non-pruned or crown-thinned trees. This counteracted the intrinsic potential of leaves in crown-reduced trees to lose more water.
- Use of artificial leaves confirmed that environmental conditions within the canopy of crown-reduced trees were less conducive to water loss to the environment outside the canopy.

Recommendations

- For practical soil moisture conservation, severe crown-reduction 70-90% of crown volume would have to be applied. Reduction of up to 50% crown volume is not consistently effective for decreasing soil drying.
- To ensure a continued decrease in canopy leaf area and maximise the period of soil moisture conservation, crown reductions should be repeated on a regular managed cycle with an interval based on monitoring re-growth.
- Crown-thinning is not an effective method to control soil drying by trees.
- More information is needed on the effect of repeated pruning to determine the impact on the root system and soil moisture conservation at the periphery of the root system.
- Root restriction within geotextile membrane lined pits may be used as an effective method for controlling shoot growth, but more knowledge is needed on the long-term integrity of the membrane, the stability and the performance of the tree.

Tree management implications

If severe crown reduction is required to alleviate subsidence risk, those trees which pose a potential risk must be identified so they can be treated. There are approximately 100 million trees in the urban environment. Of these, a large, but undefined, proportion is in sufficient proximity to a building to pose a perceived risk of damage. However, even in a drought year, the number of actual cases of subsidence is only about 50,000. The risk of a tree causing subsidence damage which is related to species, foundation depth and soil type may therefore be less than 1%. If one could identify this 1% with any reasonable accuracy, they could be pruned accordingly. However,

attempts in the past to develop methods of subsidence risk assessment have not been successful. The Arboricultural Association method of “Subsidence Risk Assessment” was withdrawn, as it was considered to be ineffective. Royal & Sun Alliance’s recent efforts to develop a statistically based model TreeRAT (Tree Risk Assessment Tool) also have not been taken beyond an initial prototype stage.

If trees that pose a risk cannot be identified, then one alternative is to treat all trees, regardless of the risk they pose. The environmental consequences of this would be catastrophic; nor could there be economic justification for any such policy as the cost of recurrent pruning would far outweigh alternative methods of remediation. For example, even pruning 1% of the tree population could cost anywhere between £50-100 million. Thus, pruning universally is unlikely to be a viable method of alleviating subsidence risk.

Some trees, for instance many of the London plane trees in city streets, are pruned on a regular basis as part of their normal management. This project has indicated that there is justification for modifying their pruning regime to reduce the risk of subsidence by reducing rather than thinning the crowns and using techniques which produce compact crowns.

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Glossary of terms

Artificial leaf: An evaporative surface that may be placed in the canopy which is used to measure boundary layer conductance (g_b) and potential water loss.

Assimilation (A): See photosynthetic fixation.

Boundary layer: An unstirred layer of air at the leaf surface or within an isolated canopy which does not readily mix with the bulk air around the tree.

Boundary layer conductance (g_b): The homogeneity of the gaseous and thermal microenvironment around a leaf determines the diffusive limitation imposed by the boundary layer. The rate of transfer of water vapour between the leaf and the bulk atmosphere can be determined using an artificial leaf.

C:N This is ratio of carbon to nitrogen within plant organic matter.

^{12}C : The most abundant stable isotope of carbon comprising 98.9% of carbon.

^{13}C : The heavy stable isotope of carbon, comprising 1.1 of carbon.

C_a : External, ambient air (a) carbon dioxide (CO_2) concentration.

Canopy architecture: The structural arrangement of branches and shoots.

C_i : Intercellular (i) carbon dioxide concentration.

C_i/C_a : The ratio of internal (i) to external (a) CO_2 concentration, which represents the internal drawdown of CO_2 within a leaf and a control point for indicating water loss against CO_2 uptake.

Climatic factors (or variables): Meteorological variables such as temperature, humidity, wind speed and sunshine hours which influence growth rate and water use of plants.

Crown reduction: A pruning method that reduces crown volume, but allows the trees natural shape to be preserved. This involves an overall reduction of both height and spread by removing the outer portions of all major branches. The normal industry standard is to aim to reduce the canopy leaf area by 30% (BS3998: 1989, Lonsdale, 1999).

Crown thinning: A pruning method that reduces the number of side branches coming off all of the major branches not affecting the original volume of the tree crown. The normal industry standard is to aim to reduce the canopy leaf area by 30% (BS3998: 1989, Lonsdale, 1999).

Diffusion: The movement of gases. When diffusion occurs gas molecules, such as water vapour, move from areas of high concentration, such as inside the leaf, to areas of lower concentration, such as the air outside the leaf.

Diurnal: Measurements made during night and day.

Discrimination (D): See isotopic discrimination.

Field capacity: The water content found when a thoroughly wetted soil has drained for about two days. It is determined in the field during the winter period and is used as a reference point against which to calculate the soil moisture deficit. It represents the maximum moisture content normally found in a particular soil.

Gas exchange: The rate of exchange of water vapour and carbon dioxide between the leaf and its surrounding atmosphere.

Growing season: The months in which trees actively grow (April to October).

Instantaneous water use efficiency (WUE_i): Determined as the instantaneous ratio of Assimilation / Evaporation (A/E), or from gas exchange measurements.

Isotope: The atomic number is determined by the number of protons in a nucleus, and for a given element different isotopes occur when the atomic mass varies because of additional neutrons. The majority (98.9%) of carbon atoms will have a mass of 12 (6 neutrons + 6 protons,) but a small number (1.1%) will have a mass of 13 (¹³C) due to an additional neutron and are stable, as compared to the radioactive decay undertaken by the much smaller proportion of ¹⁴C.

Isotopic ¹³C analysis: Mass spectrometric analysis of CO₂ usually prepared from combusted leaf organic material.

Isotopic composition (δ): The isotopic composition (δ) is the ratio of heavy to light stable isotopes within a substance relative to a standard. For carbon this would be a ratio of ¹³C/¹²C expressed relative to a standard with a known absolute isotopic composition which is arbitrarily set at 0. Ambient CO₂ (δ_p) is depleted in ¹³C by a few part per thousand (‰) compared to the reference carbonate, and therefore have negative ¹³δ C values.

Isotopic discrimination (D): Because the heavy isotope is slower to diffuse and react, discrimination arises during diffusion and fixation by Ribose-bis-phosphate-carboxylase-oxygenase (Rubisco), and so biological material is depleted in ¹³C compared to source CO₂. High discrimination leads to plant material more depleted in ¹³C (more negative ¹³δC), particularly when stomata are open with a high conductance, Ci/Ca ratio and water use. Low discrimination (plant material less depleted in ¹³C) might normally be found in leaves with low stomatal conductances and low water use. Carbon isotope discrimination (Δ) may be calculated as follows:

$$\Delta = (\delta_a - \delta_p) / (1 + \delta_p)$$

Where: Δ = discrimination, δ_a = isotopic composition of atmospheric CO₂, δ_p = isotopic composition of the plant sample.

Isotope fractionation: The change in isotopic composition associated with a specific biochemical reaction or diffusion process. Kinetic fractionations occur during the diffusion and fixation of CO₂, leading to biological discrimination. An example of a physical (equilibrium) fractionation occurs during the evaporation of water, when water molecules (H₂O) containing the more common light oxygen isotope (¹⁶O), evaporate more readily than those with the heavy isotope (¹⁸O). In a leaf, water becomes enriched in ¹⁸O during evaporation.

Isotopic signal profile: Water sources vary in isotopic composition, allowing the location of source water uptake by plants to be determined provided that sufficient shift in isotopic composition occurs between surface layers and deeper groundwater.

Leaf area: The total surface area of one side of a leaf or leaves.

Leaf area density: The total area of leaves per unit volume of the canopy.

Leaf area index (drip line): Canopy leaf area per unit ground area covered to the outer edge of the canopy.

Leaf water potential (Y): A measure of the ‘effective concentration’ of water relative to that of pure water at the same temperature and pressure. It is used in this report to relate to the driving forces for water movement. A completely non-drought stressed leaf has a theoretical water potential of zero, as a plant becomes more drought stressed the water potential decreases, (i.e. becomes more negative). A plant always equilibrates overnight with soil water potential, and so pre-dawn measurements on leaves are closely related to soil water potential.

¹⁶O: The most abundant stable isotope of oxygen.

¹⁸O: A rare heavy isotope of oxygen.

Photosynthesis: The capture of the sun’s energy and the fixation of free carbon dioxide to produce simple carbohydrates that may then be used for growth.

Photosynthetic capacity (A_{max}): The maximum rate at which carbon dioxide can be fixed during photosynthesis.

Photosynthetic enzymes: Enzymes which are specifically involved in the chemical reactions of photosynthesis. The most important of these is Ribulose-bis-phosphate carboxylase (Rubisco).

Photosynthetic fixation: Uptake of CO₂ and assimilation resulting in simple carbohydrates catalysed by Rubisco.

Photosynthetic rate: The rate at which CO₂ is fixed.

Relative humidity (rh): A measure of the water content of the atmosphere (air) relative to its total capacity.

Sap flow: The rate at which sap is transported up the trunk of the tree.

Sap flux: The total amount of sap that flow through the trunk for a given period (usually 24 h).

Season shoot development: Growth characteristics of trees over the growing season (e.g. time and rate of leaf emergence, total number of leaves per shoot, rate of shoot elongation etc.)

Soil moisture deficit (SMD): Soil moisture deficit is calculated by subtracting the total profile moisture content at an individual date from the total profile moisture content at field capacity. It is equivalent to the amount of water required to return the soil moisture content to field capacity.

Specific leaf mass (SLM): A measure of the thickness of a leaf (leaf dry weight per unit leaf area).

Stomata: Pores that occur on the underside of leaves that regulate the loss of water vapour to the atmosphere and the rate of carbon dioxide uptake from the atmosphere.

Stomatal/leaf conductance: Stomatal conductance is a measure of the capacity of leaves to lose water via transpiration (g_s) calculated from the gradient in vapour pressure between leaf interior and ambient air and the rate of evaporation, which can be corrected to describe carbon dioxide uptake (g_s). Thus, higher stomatal conductance enables a greater transpiration rate to be achieved and a more rapid exchange of carbon dioxide (i.e. CO₂ for photosynthesis) across the leaf surface, with a higher C_i/C_a ratio also related to water use and carbon isotope composition for air well stirred above leaves. Leaf conductance is the same measure as stomatal conductance except that it includes the epidermis (the contribution of the epidermis is very small relative to the stomata).

Transpiration (E): A measure of the actual water loss per unit area of leaf via the evaporation of leaf water to form water vapour which may then diffuse out of the leaf, a function of leaf and canopy boundary layers and environmental conditions.

Tree water use: Integrated flux of water removed from the soil and lost from the tree via transpiration, i.e. the total amount of water that passes from the roots, through the trunk and goes to the atmosphere from the leaves.

Vapour pressure deficit: The difference between the water vapour pressure within the intercellular spaces of the leaf (assumed to be saturated at the leaf temperature) and that in the bulk atmosphere outside the leaf.

Water use efficiency (WUE): Seasonal integration of assimilation and evaporation, or the amount of water lost relative to carbon gain (growth), whether measured instantaneously via gas exchange or integrated over longer periods of growth, for which carbon isotopes provide a proxy in leaves in well stirred air.

Water sources: Water within the soil profile may have different isotopic compositions reflecting summer or winter rains, or direct evaporation (see isotopic signal profile).