How Useful are Urban Trees?
The Lessons of the Manchester Research Project

Abstract

The physical benefits of urban trees are well known: they intercept airborne particles, thereby reducing pollution levels; they provide shade and cooling; and they intercept rainfall, reducing runoff and the chances of surface flooding. Experimental research in Manchester over the last five years has attempted to quantify some of these benefits and to compare the performance of different species and trees grown in contrasting planting regimes. Crucial to the success of this work was collaboration between local government, the voluntary sector, the tree industry and academia. It was shown that all trees provide benefits. Trees typically reduced runoff by 60%, their shade cooled urban populations by up to 4-7°C and surfaces by 15-20°C, while their evapotranspiration removed up to 50% of the energy from incoming radiation. However, performance was highly dependent on tree species and growth conditions. Faster-growing species provided twice the cooling benefits of slow-growing species, while changes in planting regime led to three-fold differences in growth rate and five-fold differences in performance. Good growth and performance were dependent on access to non-compacted, moist and well aerated soil. The research also highlighted deficiencies in our knowledge about urban trees. The results suggest that tree surveys that measure tree growth rate and record planting conditions could vastly improve our knowledge of the value of trees in our towns.

Introduction

The importance of trees in towns is well known, at least to tree professionals. As well as making the townscape more attractive and sequestering carbon, trees also confer a number of local physical benefits. Trees intercept airborne particles, reducing pollution; they provide shade, cooling local human populations; they cool the atmosphere by evaporating water; and they intercept rainfall, reducing the chances of surface flooding.

The effects of trees on the urban environment have therefore been extensively studied, not least in the excellent USDA Forest Service survey of the extent and effects of the urban forest of Chicago (McPherson *et al.*, 1994). This research has led to the development of the UFORE and iTree models, which can be used to estimate the financial benefits of urban trees.

To calculate the benefits of 'typical' trees, researchers have generally relied on one of two strategies. In some cases, they have performed small-scale surveys and experiments and scaled up to quantify the overall benefits. In other cases, they have used physical and mathematical modelling to estimate the potential benefits. For instance, carbon storage and sequestration rates have been estimated for different types of tree stands (Rowntree and Nowak, 1991) by combining tree surveys with forestry figures on the specific growth rates of trees.

The ability of trees to absorb particulate pollution, in contrast, has largely been estimated by modelling air flows and the impact of small particles on leaves. Given the complexity of airflow systems within a city, the results of such modelling cannot be totally reliable, although the effects have been separately quantified by

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Roland Ennos[1], David Armson[1] and Mohammad Asrafur Rahman[1]

[1] School of Biological, Biomedical and Evironmental Sciences, University of Hull, UK

McDonald *et al.* (2007), who compared the levels of radioactivity beneath tree stands and areas of grass caused by the deposition of particles to which radon readily becomes attached. They combined their finding that dry deposition was three times higher in trees with aerodynamic modelling to estimate that the tree cover of the West Midlands reduced PM_{10} pollution levels by 4% and that of Glasgow reduced the levels by around 2%.

The reduction in rainfall runoff has been estimated by extrapolating from the results of small-scale experiments (McPherson *et al.*, 1994) that investigated the interception of rainfall by tree canopies, although these studies did not actually measure total runoff. The effect of trees on reducing the cooling and heating costs of buildings by providing summer shade and winter shelter from the wind has also been calculated by combining small-scale experimental studies (Huang *et al.*, 1987) with larger scale modelling (McPherson *et al.*, 1994). Finally, the effect of trees in cooling the air over an entire city and thereby reducing the urban heat island effect has been quantified by large-scale climate studies with air temperatures in different parts of a city related to tree cover (McPherson *et al.*, 1994).

The benefits of this research mean that we now have useful estimates of the overall benefits of ‘typical’ urban trees or ‘typical’ areas of woodland, at least in the USA. These estimates have provided the evidence base that has driven extensive urban tree planting schemes such as that in New York. However, despite its success, this research, concentrating as it does on the effects of ‘typical’ trees and areas of urban forest, has failed to answer many of the questions that European (and indeed US) practitioners need to know before they can successfully green their cities.

First, we need to know whether trees are superior to other vegetation types, especially grass. Second, we need to know which species of trees should be planted to maximise the potential environmental benefits. Third, we need to know what size of tree is ideal: is it better to have many small or fewer large trees? We also need to know how best to plant trees, and the effect that soil conditions, cultivation techniques and irrigation will have on tree growth and environmental performance. Finally, we need to know how the performance of trees will be affected by climate change.

It is not an easy task to determine the effects of these factors on tree performance. It is difficult to instigate and perform controlled experiments on trees in environments as complex as the cityscape. Such experiments are also unlikely to be quick and easy to perform. Planting trees is expensive, and trees take many years to grow; therefore experiments will be costly and time consuming. There is also the difficultly of knowing what factors to measure and how to measure them. Finally, because there are so many factors to consider, large numbers of experiments ideally need to be performed. However, pioneering work in Manchester involving the cooperation of a range of partners from academia, the voluntary sector, local government and the tree industry have shown how some of these practical and scientific problems can be overcome. This paper describes the approach adopted and summarises the results of the work undertaken. Further research that needs to be performed is discussed, along with whether there may, in the future, be a quicker and easier way for tree professionals to quantify the benefits that individual trees provide.

Preventing Runoff

It is relatively easy technique to measure the quantity of rain that tree canopies intercept by comparing the amount of water falling into rain gauges in the open with those positioned under the tree canopy (McPherson *et al.*, 1994). However, trees can also reduce runoff by increasing infiltration, i.e., some of the rain that falls through the canopy will seep into the soil through planting holes rather than down drains. Unfortunately, it is difficult and expensive to measure infiltration or actual runoff compared with interception.

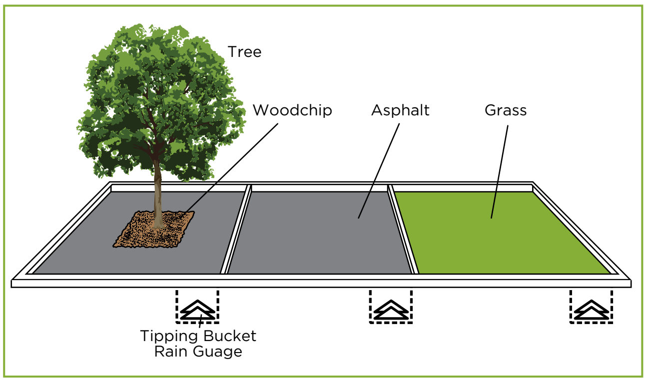

Figure 1: Diagram of one of nine test plots used to measure surface water runoff at five sites in Manchester, UK. Individual surface plots differed in the order of the areas along the plot

This problem was overcome by setting up and monitoring a number of experimental plots in South Manchester (Armson *et al*., 2013a). With funding from Manchester City Council, the European Union (INTERREG IVB), the University of Manchester and Manchester Metropolitan University, and in collaboration with the Red Rose Forest – the local community forest – nine test plots were designed and built. Each of these consisted of three 3 m x 3 m squares. One of these had a tarmac surface, the second a tarmac surface with a 3-m high field maple planted at the centre in a 1.2 x 1.2 m planting hole (to replicate a street tree scenario), the third had a grass-covered surface (Figure 1). Each square sloped gently to a drain at one corner, which emptied its contents below ground through a tipping bucket flowmeter that measured rainfall runoff from the surface. Measuring runoff daily and comparing it with actual rainfall demonstrated that the tarmac surface directed around 60% of the rainfall directly into the drains (Figure 2). In contrast, runoff was totally eliminated by the grass surface, as all of the rain percolated down into the soil. The presence of a tree, despite having a canopy of only 3 m^2, reduced runoff by a further 60% compared with the tarmac area in both summer and winter. Consequently, most of the rainwater must have infiltrated into the planting hole rather than having been intercepted by the tree canopy.

These single experiments worked well in demonstrating the large effects of trees and grass, and acted as a starting point for further hydrological investigations. More work is required to investigate the effect of other tree species, trees in different planting pits (perhaps with engineered permeable surfaces) and trees of different ages. Moreover, at £100,000, building the research plots was extremely expensive. Consequently, it has proved simpler and cheaper to make use of existing trees and previous planting programmes to investigate the cooling effects of trees.

Local Cooling

Cooling is one of the most frequently cited benefits of urban trees. However, quantifying this effect can prove difficult. In most instances, air temperature measurements are taken below and a fixed distance away from a tree, or within and outside of a park or other designated site where trees have been planted. Interestingly, when these measurements are used, the cooling effects are surprisingly small. Air temperatures within parks are typically around 1°C lower than outside (Bowler *et al*., 2010), while individual street trees have even less effect on air temperatures. The main reason is that wind readily mixes air within cities, blowing cooler air away from parks and trees and blowing warm air towards them; a process known as advection. The result is that the effects of trees and parks are dissipated across the city. Therefore, simply measuring the difference between air temperatures

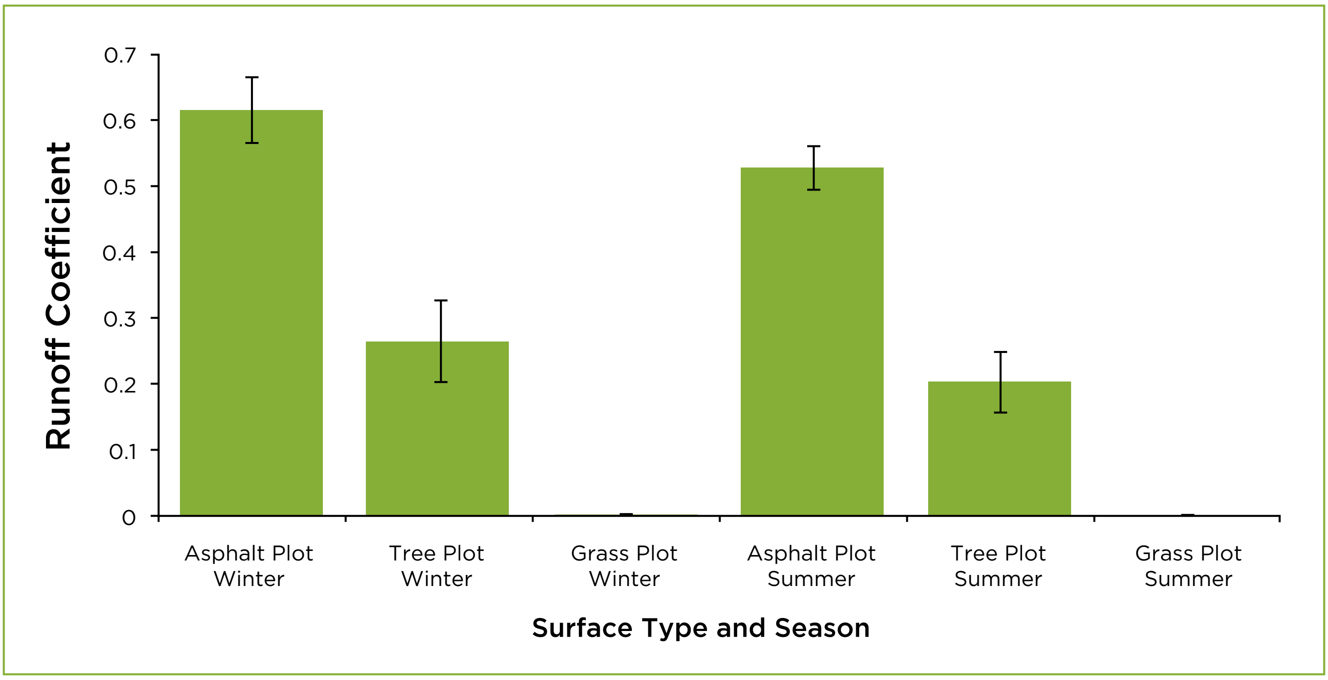

Figure 2: Effect of surface type and season on the runoff coefficients of the experimental plots. Mean and standard error shown for all types, n = 9

within and outside vegetation tends to underestimate the overall effect.

Another theoretical reason that air temperature measurements can be flawed is derived from the fields of micrometeorology and human physiology. Human perception of heat depends more on the radiant temperature of our surroundings than the actual air temperature, because humans gain and lose more heat via radiation than via convection (Monteith and Unsworth, 1990). A tree's canopy actually cools a human population down in two ways. First, it provides shade from the sun, reducing short-wave energy input (Matzarakis *et al.*, 2007). Second, as tree leaves are cooled by evapotranspiration, i.e., they lose water through their stomata, they emit less long-wave radiation (Monteith and Unsworth, 1990). This is why humans feel cooler under a tree than under the roof of a marquee.

The size of the local cooling effect was measured by a globe thermometer, an inexpensive and simple method (Thorsson *et al.*, 2007). This is in essence a normal thermometer encased in a grey sphere (a painted ping pong ball) that detects air temperature and heat from the sun and surroundings. Comparisons of measurements taken with this instrument have shown that they correlate closely with both the Index of Thermal Stress (ITS) and the Physiological Equivalent Temperature (PET) of humans (Dixin *et al.*, 2010). Measurements taken using globe thermometers demonstrated that on hot, sunny days, radiant temperatures were 5-7°C lower in the shade of mature parkland trees than in the open environment exposed to the sun's radiation (Armson *et al.*, 2012). Even immature street trees with small canopies reduced globe temperatures by 4-5°C, although the area of shade that they produced was correspondingly smaller (Armson *et al.*, 2013b). These differences are sufficient to significantly improve human thermal comfort, as humans feel hot and uncomfortable at radiant temperatures above *c.* 23°C. Consequently, during hot summers, parks and squares are areas where humans congregate to shelter in the shade of trees. Our experiments also showed that grass has little effect on radiant temperatures. Although grass surfaces are cooler than surrounding tarmac because of evaporative cooling, grass reflects more sunlight, so the net radiation striking an individual will be essentially unchanged.

Regional Cooling

While it is difficult to accurately measure the local cooling effects of trees, measuring their regional effects, i.e., how much they cool an entire city and counter the effects of the urban heat island, is even more problematic. The key to understanding how trees provide cooling is to consider the energy transferred both into and out of the ground. Cities and rural areas both receive the same amount of mainly short-wave radiation from the sun; it is the difference in what happens to this radiation in cities that alters their climate (Oke, 1987). In rural areas, much of the heat is used to evaporate water from the leaves of plants in the process of transpiration, so less is available to heat the air. In cities, in contrast, more energy is directly absorbed by buildings and roads, which warm up and heat the air by convection. Urban trees intercept the sun's radiation and evaporate water, partly reversing this effect. However, there is no individual and inexpensive method to measure the extent to which trees achieve this.

One method that has been widely used is to measure the temperature of leaves and man-made surfaces. This can be achieved using infrared thermometers that measure surface temperatures. Large geographic areas can be surveyed if infrared thermometers are mounted in aeroplanes or satellites (Leuzinger *et al.*, 2010). Typically, on a hot day it has been found that tree leaf temperatures range from 30-35°C, 10-15°C cooler than those of tarmac and concrete, which can heat up to 40-45°C. These measurements provide some indication of the cooling effectiveness of trees. However, it must be remembered that not all tree leaves are at the same temperature, as shaded leaves in the lower canopy are cooler than upper leaves (Vogel, 2013). Moreover, smaller leaves stay cooler than larger leaves even if they are not transpiring water because, having a thinner boundary layer of still air around them, they lose heat faster to the air by convection (Vogel, 2013). Consequently, leaf temperatures do not accurately correlate with the amount of convective heating they are providing to the atmosphere. Finally, both tarmac and grass are less well coupled with the air than the leaves of trees because they are within a still boundary layer of air. Therefore, simple models of cooling based on surface temperatures would be likely to underestimate the amount that trees, especially small-leaved species, heat the air by convection.

A better method to determine evaporative cooling by trees is to directly measure water loss due to transpiration. This figure can then be multiplied by the heat of the evaporation of water to calculate energy usage. One method of measuring tree water loss is to attach a sap flow gauge to the trunk. Two metal probes are inserted into the tree and the lower probe is heated in a series of pulses while the temperature of the upper probe is monitored (Granier, 1987). The warmer the upper probe, the faster the flow of water up the trunk. This technique has been found to be reasonably accurate; however, sap flow equipment is vulnerable to vandalism in cities. Therefore, in our research, we have tended to use the less direct route of measuring the stomatal conductance of individual leaves during the middle of the day and using the values to calculate water loss by initially determining the water loss per leaf and finally multiplying that by the leaf area (Rahman *et al.*, 2011). This technique was used in a series of surveys to compare the cooling potential of different tree species and investigate the influence of planting conditions on the growth and cooling of a single tree species.

Species Comparison

Five species of small street tree were investigated that had been planted by the Red Rose Forest in conventional 1.2 x 1.2 m open tree pits six years previously in the streets of South Manchester. The results (Rahman, 2013) showed that the trees with the densest canopy as measured by leaf area index – Callery pear (*Pyrus calleryana*) and hawthorn (*Crataegus laevigata*) – provided the greatest cooling on hot days of around 2 kW, twice as much as trees with less dense canopies such as crab apple (*Malus* ‘Rudolph’), rowan (*Sorbus arnoldiana*) and cherry (*Prunus* ‘Umineko’; Figure 3). All of the trees were healthy, although chlorophyll fluorescence readings showed that the rowan and cherry displayed signs of drought stress.

Planting Comparison

As well as species differences, the effects of planting regime on the growth and cooling ability of the commonly planted street tree Callery pear were also investigated. In the first study, 49 trees that the Red Rose Forest had planted in terraced streets six years previously, but using three contrasting planting techniques, were investigated (Rahman *et al.*, 2011). Trees were planted in i) conventional open pits filled with normal topsoil, ii) pits filled with Amsterdam structural soil and iii) grass verges. Measurements of the diameter at breast height (DBH) showed that the trees planted in Amsterdam soil grew at twice the rate of those grown in conventional tree

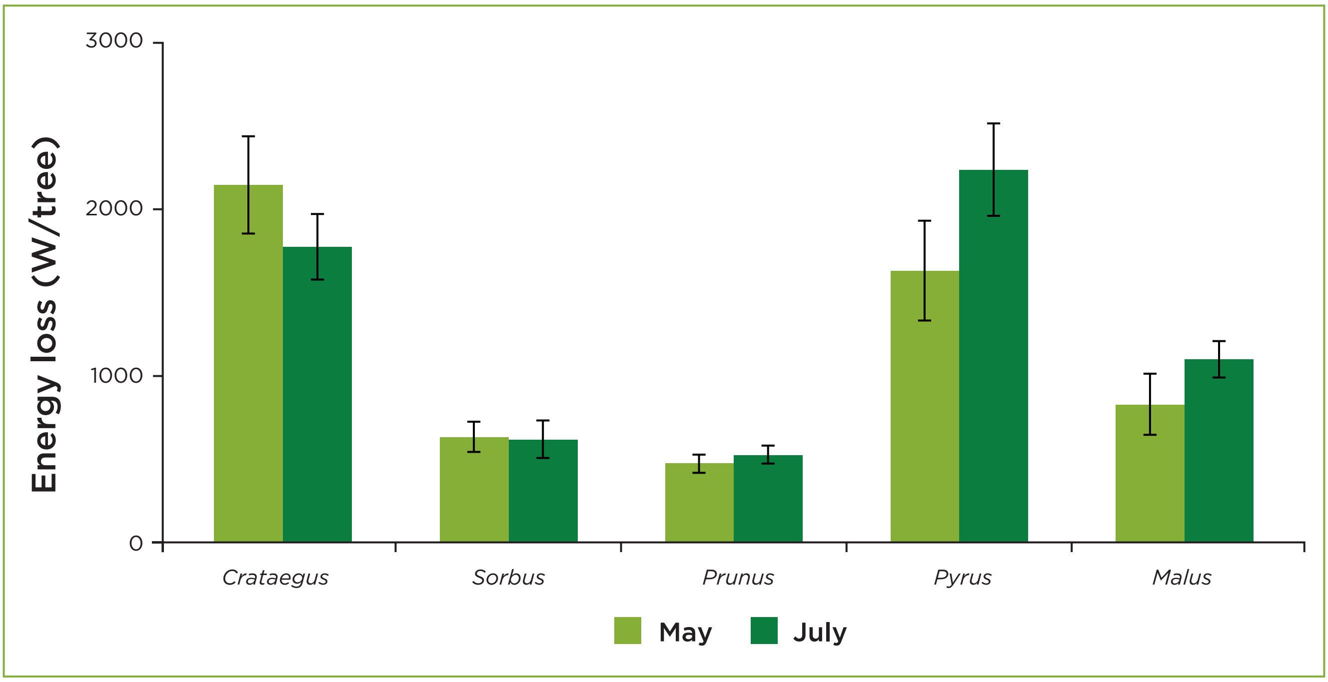

Figure 3: Evapotranspirational cooling (energy loss per tree) calculated for five different tree species grown on different streets in May and July 2011. Graphs show the mean 3 standard error (n = 12 for *C. laevigata*, 10 for *S. arnoldiana,* 10 for *Prunus* ‘Umineko’, *10* for *P. calleryana*, and 9 for *Malus* ‘Rudolph’)

pits and 1.5 times as fast as those planted in grass verges (Figure 4a). Physiological measurements also showed that the stomatal conductivity of the trees planted in Amsterdam soil was twice as high as that of the trees planted in conventional pits, providing five times the cooling of the latter at around 7kW (Figure 4b); the equivalent of two medium sized air-conditioners. Soil investigations showed that the trees in the Amsterdam soil performed better because of the resistance of this soil type to compaction, i.e., it has a lower shear strength and more porosity than conventional soils, allowing faster root growth and better root aeration.

A second study (Rahman *et al.*, 2013) investigated a range of planting techniques. The Red Rose Forest planted 15 Callery pear trees, supplied by Barcham Trees (Ely, Cambridgeshire), in three types of planting pit. Five Callery pears were planted in conventional open pits, five were grown in pits filled with structural soil and capped with permeable paving and five were planted in larger 2.8 x 1.2 m pits filled with top soil containing root cells that supported permeable paving. This last, more expensive, technique was expected to promote optimal tree growth and performance.

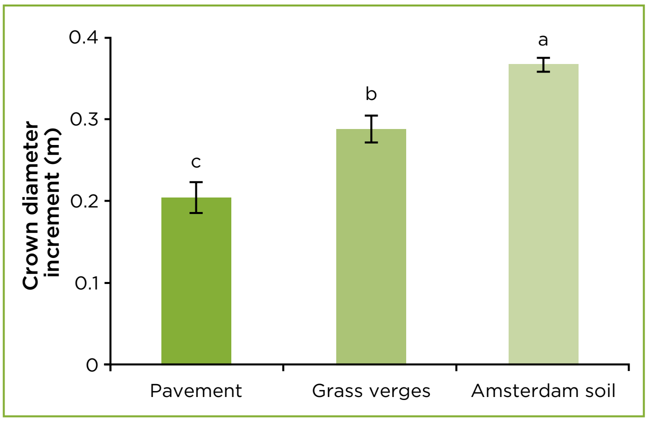

Figure 4a: Canopy growth rate per tree of *P. calleryana* trees growing in three different planting regimes (n = 15 for paved streets, 21 for grass verges and 13 for Amsterdam soil)

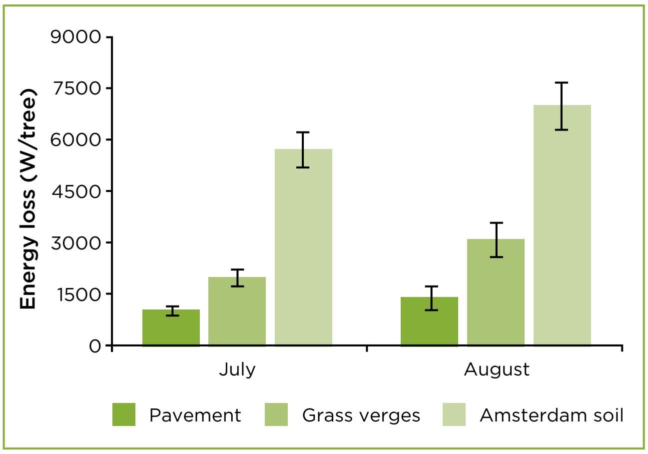

Figure 4b: Evapotranspirational cooling per tree of *P. calleryana* trees growing in three different planting regimes (n = 15 for paved streets, 21 for grass verges and 13 for Amsterdam soil)

Interestingly, the Callery pear trees in the conventional pits performed optimally (Figure 5a,b), with their DBH increasing at twice the rate of the trees in closed pits and providing four times the cooling effect after three years of growth at around 1.5 kW. The trees in the larger covered pits performed in an intermediate way. The problem with the covered pits was not inadequate water supply, as tests showed adequate levels of soil hydration; rather, it appeared that the paving was preventing oxygen from reaching tree roots, reducing their vigour. The trees in open pits performed well probably because the soil was not being compacted.

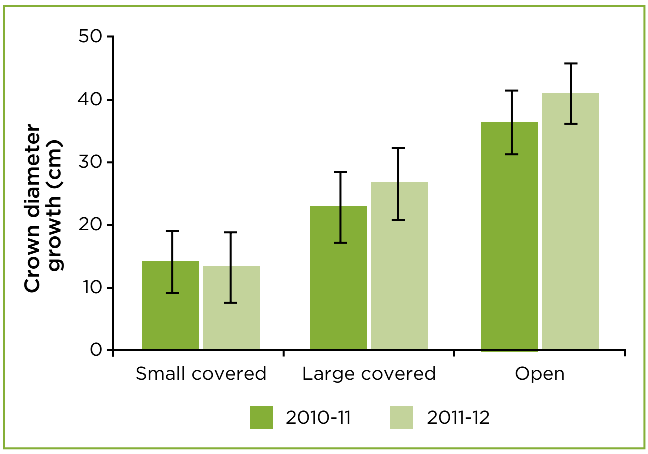

Figure 5a: Annual growth rate 9a) and evapotranspirational cooling per tree of *Pyrus calleryana* trees grown in the three pit types in 2010-2012 (n =5): (a) height, (b) DBH and (c) crown diameter increment

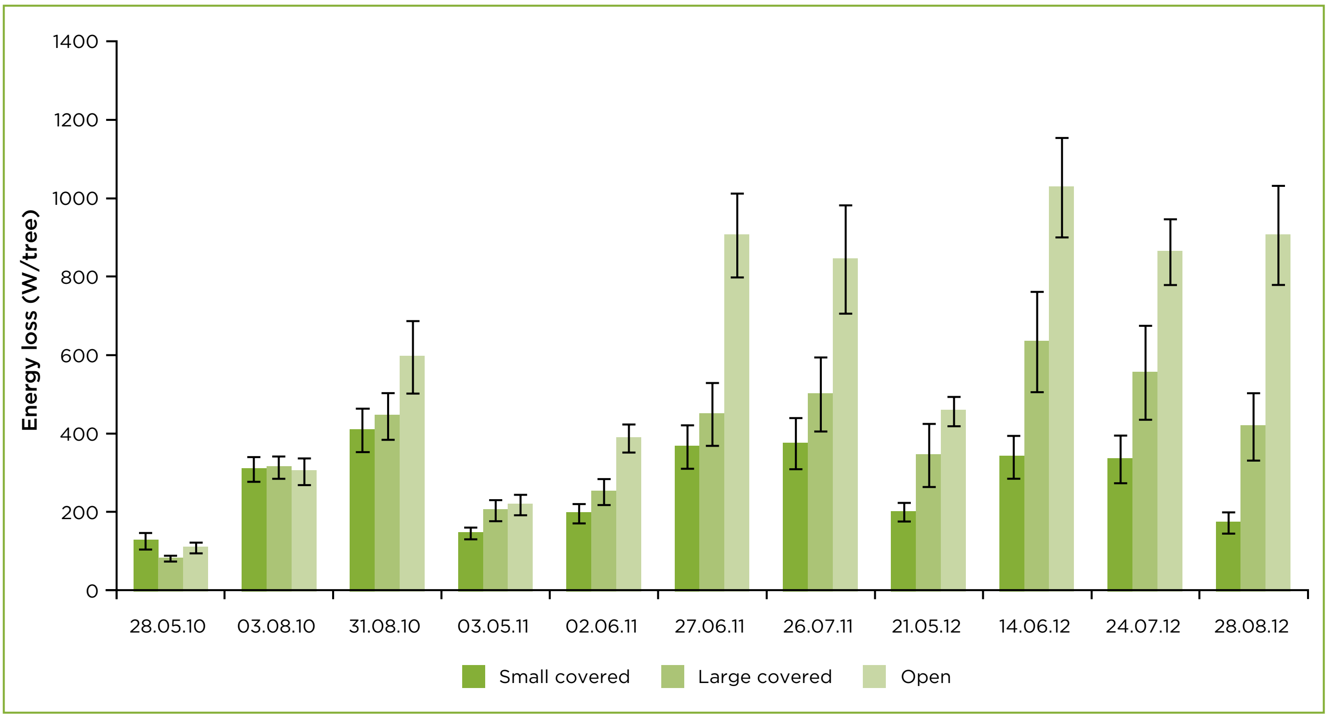

Figure 5b: Annual growth rate 9a) and evapotranspirational cooling per tree of *Pyrus calleryana* trees grown in the three pit types in 2010-2012 (n =5): (a) height, (b) DBH and (c) crown diameter increment

Conclusions and the Way Forward

The work performed in Manchester has barely scratched the surface of the topic of the physical benefits of individual trees. Clearly, more research needs to be done to quantify how beneficial trees actually are, which are the 'best' species to plant, how to plant them and how their performance depends on their age. Nevertheless, lessons have been learnt from our investigations. There are marked differences between species, with the results indicating that trees with denser canopies provide superior benefits. The crucial importance of cultivation was highlighted. The differences between the Callery pears planted in different conditions were more important than those between the different species. The importance of planting trees to ensure that the roots are not constrained by soil compaction or lack of oxygen was demonstrated.

Because of high inter- and intra-species variability, it is tempting at this initial stage to despair of ever being able to estimate the cooling effects of an individual tree without measuring them directly. Fortunately, however, one trend that has become apparent during our tests is that the trees that were healthiest and growing at the fastest rate provided the most cooling. Regression analyses examining how the whole-tree cooling provided by Callery pears depends on their growth rate (Rahman, 2013) showed that in all of the experiments there was a strong linear relationship (Figure 6a-d). The message is a useful one for tree professionals, as the data suggests that healthy, fast-growing trees are superior to unhealthy trees. This will help to provide the evidence base to persuade councils and other tree planting bodies to take greater care and provide more funds to plant trees correctly. It also suggests that it might, in the future, be possible for tree professionals, or the general public, to be able to determine how much benefit a tree is providing by measuring how fast it is growing. There are certainly good theoretical reasons for believing that this should be the case (Ennos, 2011), i.e., the faster the rate of photosynthesis, the higher the stomatal conductance for carbon dioxide uptake, and hence the greater the water loss by evapotranspiration. Presently it is not possible to directly compare the trees from our four experiments to test the idea that growth rate and cooling performance are always closely linked. In our experiments, the trees used were of different sizes and shapes and examined in different years with varying weather conditions. The crucial experiment that is required is to measure the growth rates and cooling performance of a wide range of urban tree species growing in different conditions in the same year. Such an experiment might show a close link between growth and performance.

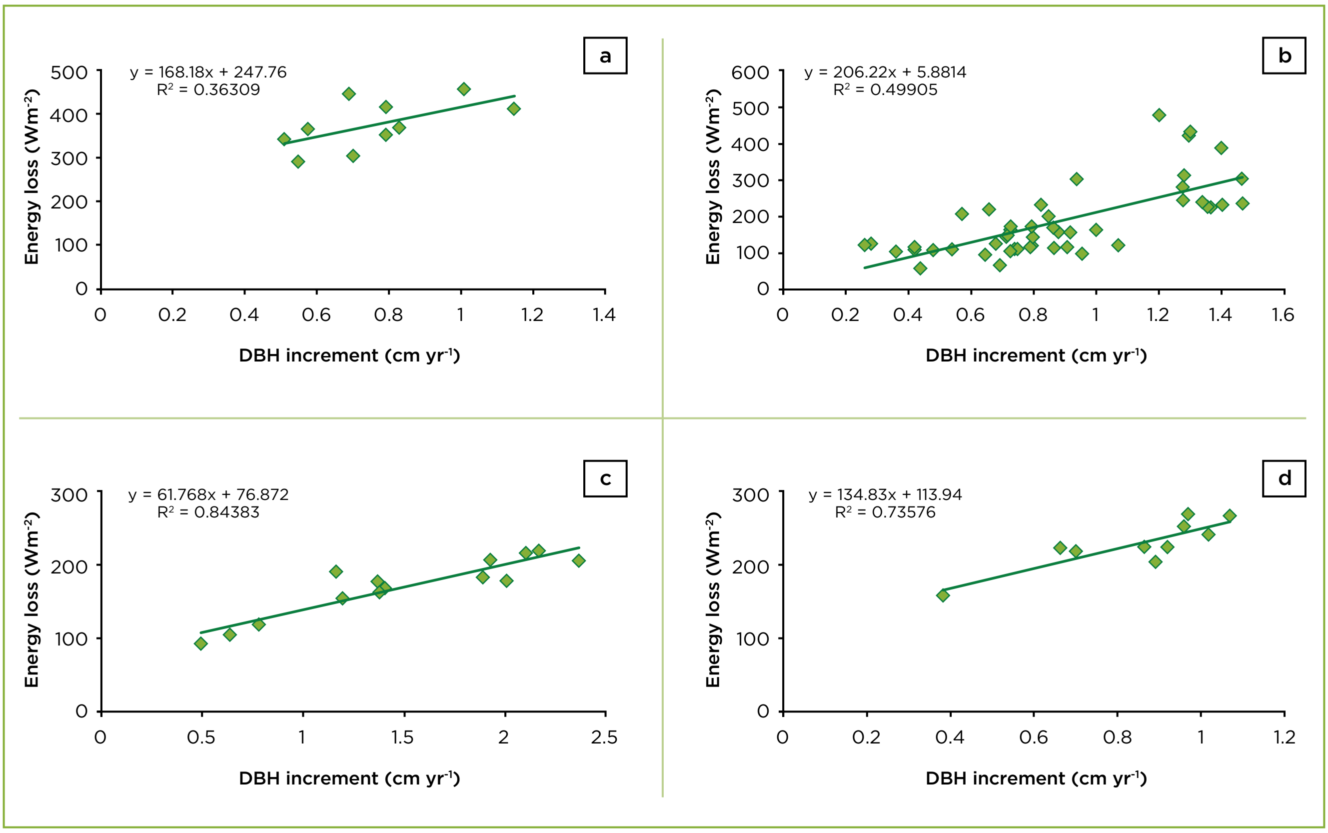

Figure 6: Regression line between energy loss per unit area and DBH increment from *P. calleryana* trees grown in four different experiments: a) Trees grown in cut-out pits in the pavements for six years; (b) trees grown in three different rooting conditions for six years; (c) trees grown in three different pit designs for three years; and (d) trees grown in control and urbanised conditions inside a botanical garden

Our research has also generated lessons on how to perform research on urban trees. First, it has shown the benefit of good planting records. If it is known how trees were initially planted and their size when planted, existing trees can be used to set up experiments that can provide quick, reliable results with no need to plant new trees and wait for them to grow. Second, it shows the benefits of partnership, with researchers, tree professionals, nurseries and members of the public working side-by-side to instigate and monitor a range of experiments. BY combining these approaches with modern methods of surveying the urban forest, such as aerial photography and remote sensing, we may be able to obtain an idea of the overall benefit that trees supply to the city and ensure that urban trees are managed for maximal benefits.

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