

# Quantifying the cooling benefits of urban trees

## Abstract

It is well known that trees can help cool cities because of the evapotranspiration of water from their leaves. However, because of the large number of factors that can affect this, such as temperature, relative humidity and soil moisture, there is no typical value of evapotranspiration for urban trees. Nor is it inexpensive or easy to measure evapotranspiration. This paper shows that because of the physics of gas flow, the rate of transpiration should be proportional to the photosynthetic rate and hence to the growth rate of a tree. Calculations using data from the literature and our own experimental results give support to this theory and suggest that, following validation and calibration, it should be possible to experimentally determine the cooling performance of urban trees merely by finding out how fast they are growing. The model also suggests that most ways of maximising growth – growing trees singly, using faster-growing species, giving trees large rooting spaces and urban soils, and providing irrigation – but not applying nitrogen fertiliser, should optimise their cooling performance. Research in this area could be carried out inexpensively and easily, and can involve a wide range of people.

## Introduction

It is well known that urban trees provide many physical benefits to cities: they sequester carbon, reduce noise, absorb particulate pollution, provide cooling and shade, and reduce storm runoff. The effects of trees on the urban environment have therefore been extensively studied, not least in the 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 (Urban Forest Effects) and i-Tree models, which can be used to estimate the financial benefits of urban trees.

The difficulties in quantifying the benefits of trees in this way cannot be overestimated. It is impossible to experimentally compare identical cities with and without trees, and it is extremely difficult and expensive to set up large-scale experiments. Researchers have had to rely on two strategies. They have carried out small-scale surveys and experiments and scaled up from there to quantify some benefits, and they have used physical and mathematical modelling to estimate others. 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 for the growth rates of trees. The ability of trees to absorb particulate pollution, in contrast, has largely been estimated by modelling the flows of air and impact of small particles on leaves. In such a complex system as airflow in a city the results of such modelling cannot be very reliable, though this effect has been separately quantified by 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<sub>10</sub> pollution levels by 4% but that of Glasgow, by only around 2%.

The reduction in rainfall runoff is extrapolated from the results of small-scale experiments (McPherson *et al.*, 1994) that investigated the interception of rainfall by tree canopies, though these studies did not actually measure the runoff itself. We are currently finding that other factors, such as the presence of planting holes and other permeable surfaces, reduce runoff by even more than their estimates would suggest.

The effect of trees on reducing the cooling and heating costs of buildings by providing summer shade and winter shelter from wind was also calculated by combining small-scale experimental studies (Huang *et al.*, 1987) with larger-scale modelling (McPherson *et al.*, 1994). Finally, the effect

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of trees in cooling the air over the whole city and hence reducing the urban heat island effect was quantified by large-scale climate studies; air temperatures in different parts of the city were related to the tree cover (McPherson *et al.*, 1994).

All of this hard work means that we now have good estimates of the overall benefits of urban trees, at least in the USA, which 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 American) practitioners really need to know before they can successfully green their cities. Are trees actually better than other types of vegetation, especially grassland, at providing cooling? Which species of trees provide the greatest cooling benefits? Is it better to have many small or fewer large trees? What effect will soil conditions and irrigation have on the cooling benefits that trees confer? And how will climate change affect the growth and cooling effectiveness of trees? Here I show that, despite the apparent complexity of the situation, understanding the physics of the urban climate and the physiology of trees can give us an incredibly inexpensive and simple method of answering these questions. By involving not only scientists but also tree professionals and the general public in new research projects based on this method, we can rapidly improve our knowledge of the benefits of urban trees and revolutionise people's perceptions of the role of science in our lives.

## Urban trees and cooling

The effect of trees on urban climate is ideally approached by comparing the energy balance of rural and urban areas. Though heating, air conditioning and transport all produce energy in the city, this is a surprisingly small component of their heat balance; anthropogenic heat output is around  $50 \text{ Wm}^{-2}$ . Except in winter this is dwarfed by the energy we receive from the sun, which even in the UK peaks at over  $800 \text{ Wm}^{-2}$ . The difference between town and country is therefore mostly due to what happens to the sun's energy in the two environments.

In rural areas, around 20–25% of the incoming short-wave radiation is reflected back into the sky by grass and 15% by trees. Of the energy that is absorbed, over a half is often used to evaporate water from leaves, a process known as evapotranspiration (Oke, 1987). This cools the vegetation, so it radiates little long-wave radiation and even less energy remains to heat the air by convection and to heat the soil by conduction.

In cities, where vegetation has been replaced by buildings and roads, the energy balance is dramatically altered. Dark man-made materials have a lower albedo than vegetation, so around 15% of the sun's radiation is reflected, and even less in high-rise cities where light is reflected down into urban 'canyons'. Almost all of the absorbed energy is used to heat up the dry roads and roofs, where it is either stored in bricks and mortar or heats the air above, raising daytime surface and air temperatures well above that of the surrounding countryside. At night the situation can become worse, since cities also cool down more slowly; there is more heat stored in the buildings to dissipate, there is more pollution to trap long-wave radiation, and within urban canyons less of the cool sky is visible, so less radiation can escape. The result is the development of a summer urban heat island which can cause a rise in air temperatures of up to  $7^\circ\text{C}$  in large cities (Wilby, 2003).

It is easy to understand that incorporating vegetation into cities should reduce the urban heat island, largely because it increases evapotranspirational cooling. Unfortunately, though, it appears at first glance to be extremely difficult to quantify how great this effect will be, since evapotranspiration can be affected by a large number of interacting factors. First, it will depend on the weather: on the temperature, relative humidity, the amount of incoming radiation, windspeed and air turbulence. It will also depend on the properties of the vegetation itself: on the crown area, leaf area index, height of the leaves, stomatal conductance, and hydraulic resistance of the shoot and root. Finally, it will depend on the soil conditions: on its dryness, compaction and hydraulic conductivity. If we had to measure all of these factors it would be impossible to make sensible estimates for what is occurring even for smaller plants.

## Estimating and measuring evapotranspiration of vegetation

To estimate the evapotranspiration of large areas of vegetation, environmental physicists and micrometeorologists have approached the problem from a purely physical standpoint; they have considered the energy changes at the surface of evaporating vegetation. The rate of evaporation from a wet surface exposed to air which is not fully saturated is given by the Penman equation (Monteith and Unsworth, 1990).

$$\lambda E = \frac{mR_n + \rho c (\delta e) g_a}{m + \gamma} \quad 1)$$

where  $\lambda$  is the latent heat of water (around  $2.43 \text{ MJ kg}^{-1}$ ),  $E$  is the rate of loss of water per unit area ( $\text{kg m}^{-2}\text{s}^{-1}$ ),  $m$  is the

slope of the saturation vapour pressure curve ( $\text{Pa K}^{-1}$ ),  $R_n$  is the net irradiance ( $\text{W m}^{-2}$ ),  $\rho$  is the density of air ( $\text{kg m}^{-3}$ ),  $c$  is the specific heat of air ( $\text{J kg}^{-1} \text{K}^{-1}$ ),  $\delta e$  is the vapour pressure deficit (or difference between vapour pressure of air and saturation) (Pa),  $g_a$  is the conductance of the air around the surface ( $\text{m s}^{-1}$ ) and  $\gamma$  is the psychrometer constant ( $c\rho/\lambda e$ ) (around  $66 \text{ Pa K}^{-1}$ ).

The Penman equation shows that water loss is the sum of two components: that due to the solar radiation heating the surface and that due to the fact that water evaporates even from unheated surfaces. As a result the rate of water loss depends predictably on the level of sunlight, on the air temperature, on the dryness of the air, on the position of the surface, and on the windspeed. However, the equation has to be modified for plants, which have lower water loss than a wet surface because of the resistance of their stomata to water loss. This results in the well-known Penman-Monteith equation (Monteith and Unsworth, 1990).

$$\lambda E = \frac{mR_n + \rho c (\delta e) g_a}{m + \gamma(1 + g_a/g_s)} \quad 2)$$

where  $g_s$  is the stomatal conductance.

By making assumptions about the way wind varies close to a rough surface and estimating the stomatal conductance of crops, agronomists can incorporate continuous measurements from weather stations into this equation to estimate the rate of water loss from a layer of well-watered grass. This is known as the reference evapotranspiration  $ET_0$  (Allen *et al.*, 1998).

To verify this estimate and measure actual values of evapotranspiration for different types of vegetation cover, meteorologists have devised several experimental techniques which can be used over large areas of vegetation. The most commonly used is the eddy correlation method (Oke, 1987) in which the vertical velocity and relative humidity of air is measured above the stand, and combined to calculate the upward rate of water movement. Measurements using eddy correlation confirm that the Penman-Monteith equation does accurately estimate water loss from well-watered grass (Allen *et al.*, 1998). The rates of evapotranspiration from other plants have also been measured. They tend to be lower in crops with low stomatal conductance (e.g. drought-resistant crops), and higher in ones with high stomatal conductance. The three-dimensional shape of the plants is also important as this affects the canopy conductance. In low-growing grasses there is low conductance due to the barrier of still air near the ground. In isolated trees, in contrast, the conductance is much higher, since they protrude out of the boundary layer

into the wind. The evapotranspiration of a range of species is calculated by incorporating a crop factor  $K_C$  into the Penman-Monteith equation (Allen *et al.*, 1998) where

$$E_T = ET_0 \times K_C \quad 3)$$

Tables of crop factors are given by Allen *et al.* (1998) and tend to be around or less than 1 for most crop plants but can exceed 1 for some orchard trees.

The crop factors given are for well-watered plants. Drought reduces evapotranspiration below the reference figure, lowering  $K_C$  because of the reduced conductance of the stomata as the plant shuts down. To calculate the evapotranspiration of droughted crops it is usual to reduce the evapotranspiration by a factor proportional to the matric potential of the soil (Rowell, 1994; Allen *et al.*, 1998).

The results of these types of studies have proved to be reliable and extremely useful for farmers planning irrigation programmes and greenkeepers planning watering regimes for golf courses. However, they are less useful for calculating the evapotranspiration of urban trees. There are limited data for the crop factors of urban trees in the literature, and studies using eddy covariance are expensive. In any case, urban trees are rarely found in continuous stands; they are more often planted in small groups or singly. The evapotranspiration of isolated trees has in fact rarely been investigated, though the physical analysis of the meteorologists suggests that isolated urban trees should have higher rates of evapotranspiration per unit canopy area than continuous forests or grass. This is because they will encounter dry air from outside the stand, and this advection will increase evapotranspiration. This should result in what are known to meteorologists as the clothes-line and oasis effects, but the size of the increases that will result are uncertain. Some methods are therefore required to estimate or measure the evapotranspiration from individual trees.

## Estimating and measuring evapotranspiration of individual trees

Plant physiologists have devised some fairly straightforward ways of directly measuring the evapotranspiration of a plant. For small containerised plants, including small trees, it is possible to continuously monitor the weight of the plant and its pot (Kjelgren and Montague, 1998; Montague *et al.*, 2004). For larger trees this is impractical. An alternative method is to attach a porometer or IRGA to a leaf to measure its stomatal conductance (Lambers *et al.*, 1998). If

you also measure the leaf temperature, air temperature, atmospheric pressure, relative humidity and the leaf area of the tree you can use this result to calculate the instantaneous rate of water loss. Unfortunately, this method is expensive, time-consuming and impractical for continuous monitoring. A final method has that been devised that will allow continuous monitoring of water loss is to use sap flow meters (Pataki *et al.*, 2011). These are electrically heated collars that can be attached to the trunk; they apply bursts of heating to it, warming the sap within, while the apparatus monitors the temperature higher up the trunk, allowing the velocity and hence volume flow of water up the trunk to be calculated. This technique is becoming increasingly common, having being used extensively in forests and orchards, but can be rather complicated and expensive to perform, and highly vulnerable to vandalism.

When these techniques have been applied to measure the evapotranspiration of urban trees, the results have been extremely variable. For instance Montague *et al.* (2004) found that water loss varied widely between species, and there were large differences between trees growing over grass and asphalt (Kjelgren and Montague, 1998). Similarly our measurements of *Pyrus calleryana* Chanticleer street trees (Rahman *et al.*, 2011) found large differences in growth and evapotranspiration rates between trees grown in different soil conditions. We found that trees planted in Amsterdam soil had twice the rate of diameter breast height growth as ones grown in conventional tree pits, probably because the lack of soil compaction had allowed their roots to grow more rapidly. The trees in Amsterdam soil also had twice the stomatal conductance, and because of their greater crown diameter and leaf area index were transpiring at five times the rate of trees growing in conventional soil pits. At midday on sunny days they were providing some 7 kW of cooling (compared to 1.5 kW for trees in conventional tree pits), and losing heat at a rate of 1105 W m<sup>-2</sup>, over three times that of a reference crop of grass. Finally, in their survey of trees across Los Angeles Pataki *et al.* (2011) found tenfold differences in evapotranspiration between trees, depending on their location and the level of irrigation with which they were supplied. It is plain, therefore, that there are no 'typical values' of evapotranspiration rate that can be applied to urban trees.

## The solution

Fortunately, there is a simple way of overcoming the uncertainties about evapotranspiration which is related to the way in which plants control their water loss and the physics of the movement of gases. Plants open their stomata to facilitate CO<sub>2</sub> access, which is used in photosynthesis, but this has the disadvantage that at the same time it releases

water vapour. The rate of evapotranspiration of a plant is therefore directly proportional to the rate at which carbon dioxide enters: in other words its photosynthetic rate. The water use efficiency of photosynthesis in conventionally photosynthesising C<sub>3</sub> plants can be given by the equation:

$$WUE = 1.6c P_a / (e^*_L - e) \quad 4)$$

(Farquhar *et al.*, 1980; Sinclair *et al.*, 1984). Here P<sub>a</sub> is the ambient concentration of CO<sub>2</sub> in the atmosphere, c is 1 minus the ratio of internal to external CO<sub>2</sub> concentration ((1 - P<sub>i</sub>/P<sub>a</sub>), which is around 0.3 for conventionally photosynthesising C<sub>3</sub> plants), e<sup>\*<sub>L</sub></sup> is the saturation vapour pressure at leaf temperature and e is the vapour pressure of the atmosphere. Equation 4 shows that the water use efficiency must be pretty similar for all trees. They could increase efficiency by keeping their leaves cooler (and so reduce e<sup>\*<sub>L</sub></sup>). They could also increase the level of the carbon fixing enzyme Rubisco (and hence the nitrogen concentration) in their leaves, so reducing P<sub>i</sub> and increasing c. However, both of these effects are limited. Consequently, the water use efficiency of conventionally photosynthesising C<sub>3</sub> plants (such as trees and temperate grasses) is remarkably constant, from 2 to 4 x 10<sup>-3</sup> moles CO<sub>2</sub> assimilated per mole H<sub>2</sub>O lost (Farquhar *et al.*, 1980). For each mole of CO<sub>2</sub> assimilated, 250 to 500 moles of H<sub>2</sub>O are lost (Field *et al.*, 1983).

How can this help us? Continuous monitoring of photosynthesis is impractical, but we can readily measure tree growth and carbon sequestration over the season. We also need to be able to relate this to photosynthesis. Studies on the net and gross primary productivity of forests (Waring *et al.*, 1998) and experimental investigations on young poplar and Douglas fir trees (Rippulone *et al.*, 2004) have shown that approximately 50% of photosynthesis is converted into biomass production so that the water use efficiency in terms of dry biomass production WUE<sub>B</sub> is 1.5 to 2.5 g biomass kg<sup>-1</sup> water loss. Inverting the equations provides the following estimates for water loss per unit of above-ground biomass sequestration.

$$\text{Water loss} = 0.4 \text{ to } 0.66 \text{ tonnes H}_2\text{O kg}^{-1} \text{ biomass sequestered } 5)$$

Since evaporation of water requires 2.43 x 10<sup>3</sup> J g<sup>-1</sup>, it is also straightforward to calculate the cooling provided.

$$\text{Cooling} = 1.0 \text{ to } 1.6 \times 10^9 \text{ J kg}^{-1} \text{ biomass sequestered } 6)$$

## Discussion

The theory seems simple and compelling, but how realistic are these figures? There are two ways of judging these

estimates: by comparing the predicted water losses with actual measurements and by comparing cooling rates with actual measurements.

Consider the water losses of a short rotation coppice, sequestering biomass at the rate of 10 tonnes  $\text{ha}^{-1}\text{a}^{-1}$  or 1.0  $\text{kg m}^{-2}\text{a}^{-1}$ . It should lose water at a rate of 0.4 to 0.66 tonnes  $\text{H}_2\text{O m}^{-2}\text{a}^{-1}$  or over a 180 day season at a rate of 2.2 to 3.3  $\text{mm d}^{-1}$ , which is in good agreement with measured values (Guidi *et al.*, 2008). This water loss would provide a mean cooling over a 16 hour day of  $1.0$  to  $1.6 \times 10^9 / (180 \times 16 \times 60 \times 60) = 96$  to  $154 \text{ W m}^{-2}$ . Peak cooling rates are probably around 4 times this value: 380–610  $\text{W m}^{-2}$ , which is somewhat lower than the values we obtained for our fast-growing *Pyrus* trees. Contrast that with a typical area of deciduous forest that is sequestering dry mass at a rate of 2 tonnes  $\text{ha}^{-1}\text{a}^{-1}$  or 0.2  $\text{kg m}^{-2}\text{a}^{-1}$ . It will provide cooling at a rate of 2 to 3.6  $\times 10^8 \text{ J m}^{-2}\text{a}^{-1}$ . Given that cooling only occurs during the day when the forest is in leaf this means a mean daily cooling rate of 2.0 to 3.6  $\times 10^8 / (180 \times 16 \times 60 \times 60) = 19$  to 31  $\text{W m}^{-2}$ . Peak cooling rates are probably around 4 times this value: 75–125  $\text{W m}^{-2}$ , which is around 10–16% of UK peak radiation input, similar to the values obtained for forests (Oke, 1987).

What about urban trees? Using equations 5 and 6, and the figures for the sequestration rates of areas of urban forests from Rowntree and Nowak's (1991) study, an average stand of trees, sequestering carbon at 0.3 tons per acre, would be laying down dry biomass at a rate of 1.87 tonnes  $\text{ha}^{-1}$ . It would therefore have been providing an average cooling over the day during the growing season of 18–29  $\text{W m}^{-2}$ . Fast-growing young stands (Type 1) would produce higher rates of cooling of 45–73  $\text{W m}^{-2}$ . From their figures, the cooling of a single sugar maple can also be calculated. As its sequestration rate increases up to a peak at age 70 years of 200 pounds of carbon per year, or 90 kg, it would provide an average rate of cooling of 10–17 kW.

These results, though promising and plausible, are only estimates. The model needs to be verified and calibrated by carrying out studies in which the growth and sequestration rates of a range of urban trees are measured, and related to sap flow measurements of their annual water loss.

Assuming that the results of such a study verify the model, the implications of the theory are profound, and lead to several predictions. The first prediction is that because trees project out of the boundary layer and can grow faster than grass, trees have the potential to cool cities at many times the rate of grass swards of the same surface area. The second prediction is that isolated trees, which can capture

several times more sunlight, grow several times faster and cast shade over several times the ground area than canopy trees, should provide greater cooling benefits per unit crown area. The third is that fast-growing tree species will provide greater cooling benefits than slow-growing species as long as they are kept supplied with sufficient water. This explains why fast-growing but water-demanding plane trees are planted in urban areas in Mediterranean countries, rather than drought-tolerant species. The fourth prediction, though, is that simply planting urban trees is not enough; they must also be sited and maintained in such a way as to maximise their growth rate to allow them to provide the maximum cooling benefit. Fortunately, this is something that would be welcomed in any case by tree professionals. Several techniques could be used to ensure trees perform well. They could be grown in large volumes of urban soils that resist compaction and hence allow rapid root growth. They could be grown beneath large areas of permeable paving, and pavements could be contoured in towards their planting holes to maximise the input of rainwater. Of course this would have the added advantage that it would also minimise runoff to drains. Finally, as in Mediterranean countries, they could be provided with ample irrigation, possibly from stormwater runoff. The one method of stimulating tree growth that would be unlikely to improve cooling would be to supply them with larger amounts of nitrogen fertiliser. Though this would probably improve their growth rate, it would also increase their water use efficiency, so any effect on transpiration and cooling rates would be small.

The theory also provides us with the potential opportunity to determine the cooling power of our current tree stock merely by measuring its rate of growth and carbon sequestration. Measuring tree growth and estimating the rate of sequestration of biomass are well within the capabilities of tree professionals, and even trained members of the general public. These could then be converted to the cooling power of the trees. There is an opportunity, therefore, to develop projects countrywide to measure the environmental benefits of our trees and determine how best they can be maximised. At the same time such projects would also give a wide range of people the opportunity to become involved in citizen science and in the care of their local environment.

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