Effects of Species and Rooting Conditions on the Growth and Cooling Performance of Urban Trees

A thesis submitted to the University of Manchester for the degree of Doctor of Philosophy in the Faculty of Life Sciences.

2013

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## Table of Contents

List of Figures .................................................................................................................. 6  
List of Tables ..................................................................................................................... 10  
Abstract ............................................................................................................................. 11  
Declaration ......................................................................................................................... 12  
Copyright Statement ......................................................................................................... 13  
Acknowledgements ............................................................................................................. 14  
Thesis Organisation ........................................................................................................... 15  
Chapter 1 .......................................................................................................................... 17  
General Introduction ......................................................................................................... 17  
  1.1 Climate change and urbanization ............................................................................... 18  
      1.1.1 Climate change ................................................................................................. 18  
      1.1.2 Urbanization ..................................................................................................... 19  
      1.1.3 The Urban heat island effect ............................................................................ 20  
  1.2 Vegetative cooling in urban areas ........................................................................... 23  
      1.2.1 Evapotranspiration .......................................................................................... 26  
      1.2.2 Shading effect ................................................................................................... 28  
  1.3 Quantifying the cooling effects of trees .................................................................. 29  
  1.4 Modelling the impact of vegetation in the urban cooling ....................................... 32  
  1.5 Comparing the cooling efficiency of trees ............................................................... 36  
      1.5.1 Species differences ......................................................................................... 36  
      1.5.2 Growth conditions ......................................................................................... 40  
      1.5.3 Climate change feedback ................................................................................ 42  
  1.6 Aims, objectives and chapters .................................................................................. 44  
Chapter 2 .......................................................................................................................... 48  
A comparison of the growth and cooling effectiveness of five commonly planted urban  
  tree species ....................................................................................................................... 48  
  Abstract ............................................................................................................................ 50  
  1. Introduction .................................................................................................................. 51  
  2. Methods ....................................................................................................................... 54  
      2.1 Site and species selection .................................................................................... 54  
      2.2 Tree growth and soil shear strength .................................................................... 57  
      2.3 Total stored CO₂ calculation ............................................................................... 57  
      2.4 Crown, Soil and Physiological measurements .................................................. 58  
      2.5 Soil moisture content and leaf area index (LAI) ................................................ 58  
      2.6 Leaf physiology ..................................................................................................... 59  
      2.7 Leaf chlorophyll fluorescence (Fv/Fm) .................................................................. 61  

2.8 Leaf chlorophyll analysis .................................................................62
2.9 Foliar nutrient analysis ................................................................62
2.10 Statistical analysis .......................................................................63
3. Results ............................................................................................63
  3.1 Tree growth and carbon sequestration .......................................63
  3.2 Soil moisture content and shear strength ..................................65
  3.3 Leaf physiology ..........................................................................67
  3.4 Relationship between stomatal conductance and DBH increment ....68
  3.5 Evapotranspirational cooling .......................................................68
  3.6 Chlorophyll fluorescence (Fv/Fm) ................................................70
  3.7 Leaf chlorophyll content ..............................................................70
  3.8 Foliar nutrient analysis ..............................................................72
4. Discussion ......................................................................................73
Acknowledgments ..............................................................................77
References ........................................................................................78
Chapter 3 ..........................................................................................86

Effect of Rooting Conditions on the Growth and Cooling Ability of Pyrus calleryana .86

Abstract ..........................................................................................88
1. Introduction .....................................................................................89
2. Methods .........................................................................................91
  2.1 Site selection and Pyrus calleryana trees .....................................91
  2.2 Tree growth and phenology .........................................................92
  2.3 Soil shear strength and moisture content .....................................93
  2.4 Foliar nutrient analysis ...............................................................93
  2.5 Soil nutrient analysis .................................................................94
  2.6 Leaf Physiology ...........................................................................94
  2.7 Statistical analysis .....................................................................96
3. Results ............................................................................................96
  3.1 Tree growth and phenology .........................................................96
  3.2 Soil shear strength and relationship with the growth parameters ....99
  3.3 Soil moisture content .................................................................101
  3.4 Foliar nutrient status .................................................................101
  3.5 Soil nutrient status ....................................................................102
  3.6 Leaf Physiology ..........................................................................103
  3.7 Evapotranspirational Cooling ....................................................104
4. Discussion ......................................................................................105
Acknowledgments ..............................................................................110
List of Figures

Chapter 1
Figure 1.1: A schematic diagram of urban heat island (adopted from Mayor of London, 2006). 21
Figure 1.2: Diagram showing the comparison of energy exchange between rural landscapes (A) and an urban landscape (B) (adopted from Whitford et al., 2001). 22
Figure 1.3: Types of energy balance (A) Country sites – day time (B) Night time (C) Urban areas – day time (D) Night time (modified from Rouse, 1978). 25
Figure 1.4: A schematic diagram showing tree transpiration process (Source: http://science.yourdictionary.com/transpiration) 27
Figure 1.5: Water movement in the soil-plant-atmosphere continuum (source: http://bioscvilla-sya.blogspot.co.uk) 28
Figure 1.6: Framework of the Energy Balance Model (adapted from Whitford et al., 2001) 33
Figure 1.7: A schematic diagram of conflicts between tree root development and underground utilities in a built environment (adopted from Jim, 1998). 41

Chapter 2
Fig. 1 Location map for the city of Manchester showing the two sample site areas – Whalley Range and Levenshulme. 56
Fig. 2 Differences in growth and stored CO₂ in five different tree species grown on different streets of Manchester, UK. Annual growth increments (2005–11) in (a) height, (b) DBH and (c) crown diameter and (d) Total CO₂ stored in April, 2011. Graphs show means ± standard error (n = 27 for C. laevigata, 15 for S. arnoldiana, 13 for Prunus ‘Umíneko’, 26 for P. calleryana, and 14 for Malus ‘Rudolph’). 64
Fig. 3 Mean LAI in May and July, 2011 of five different tree species grown on different streets of Manchester, UK. Graph shows means ± standard error (n = 12 for C. laevigata, 10 for S. arnoldiana, 10 for Prunus ‘Umíneko’, 10 for P. calleryana, and 9 for Malus ‘Rudolph’) 65
Fig. 4 Soil moisture content in May and July, 2011 in the top 20 cm around the tree pits of five different tree species. Graph shows means ± standard error (n = 12 for C. laevigata, 10 for S. arnoldiana, 10 for Prunus ‘Umíneko’, 10 for P. calleryana, and 9 for Malus ‘Rudolph’) 66
Fig. 5 Leaf physiological parameters of five different tree species grown on different streets in May and July, 2011: (a) midday leaf water potential; (b) stomatal conductance. Graphs show means ± standard error (n = 12 for C. laevigata, 10 for S. arnoldiana, 10 for Prunus ‘Umíneko’, 10 for P. calleryana, and 9 for Malus ‘Rudolph’) 67
Fig. 6 Relationship between DBH increment and stomatal conductance of 68
five different tree species grown on different streets in May and July, 2011

Fig. 7 Evapotranspirational cooling calculated for five different tree species grown on different streets in May and July, 2011 (a) energy loss per unit leaf area; (b) energy loss per tree. Graphs show means ± standard error (n = 12 for *C. laevigata*, 10 for *S. arnoldiana*, 10 for *Prunus ‘Umineko’*, 10 for *P. calleryana*, and 9 for *Malus ‘Rudolph’*)

Fig. 8 Differences in leaf chlorophyll content of five different tree species grown on different streets of Manchester in May, July and August, 2011. (a) Total chlorophyll (a+b) and (b) Chlorophyll a: b. Graphs show means ± standard error (n = 12 for *C. laevigata*, 10 for *S. arnoldiana*, 10 for *Prunus ‘Umineko’*, 10 for *P. calleryana*, and 9 for *Malus ‘Rudolph’*)

Chapter 3
Figure 1: Differences in growth and morphology of *P. calleryana* grown on three different planting regimes. Annual growth increments (2004 – 10) in a) height b) DBH and c) crown diameter and d) LAI of the crown in May 2010. Graphs show means ± standard error (n = 15 for paved streets, 21 for grass verges and 13 for Amsterdam soil).

Figure-2: Annual lateral shoot extension in the previous three years (2007 - 09) of *P. calleryana* grown in different planting regimes. Graphs show means ± standard error (n = 15 for paved streets, 21 for grass verges and 13 for Amsterdam soil).

Figure-3: Shear strength of soil around *P. calleryana* trees grown in different planting regimes. Graphs show means ± standard error (n = 15 for paved streets, 21 for grass verges and 13 for Amsterdam soil).

Figure-4: Effect of soil shear strength on the growth and morphology of *P. calleryana* (a) diameter growth and (b) LAI increase.

Figure-5: Soil moisture content in the top 20 cm and at 80 cm depth around the bases of *P. calleryana* trees grown in different planting regimes. Graphs show means ± standard error (n = 15 for paved streets, 21 for grass verges and 13 for Amsterdam soil for 20 cm depth and n = 6, 6 and 5 respectively for 80 cm depth).

Figure-6: Leaf physiological parameters of *P. calleryana* trees grown in different planting regimes at three different times of the year (May, July and August, 2010): (a) midday leaf water potential; (b) stomatal conductance. Graphs show means ± standard error (n = 15 for paved streets, 21 for grass verges and 13 for Amsterdam soil).

Figure-7: Evapotranspirational cooling calculated for *P. calleryana* trees growing in three different planting regimes (n = 15 for paved streets, 21 for grass verges and 13 for Amsterdam soil).
Chapter 4
Figure 1: Cross-sectional design of the three pit types (adapted from tree planting design for Red Rose Forest drawn by Ombler Iwanowski Architects).
Figure 2: Annual growth rate in Pyrus calleryana trees grown in the three pit types in 2010-2012 (n =5): (a) height, (b) DBH and (c) crown diameter increment.
Figure 3: LAI of Pyrus calleryana trees grown in the three pit types in 2010-2012 (n=5)
Figure 4: Leaf water potential of Pyrus calleryana trees grown in the three pit types in 2010-2012 (n=5) a) mid day b) predawn
Figure 5: Stomatal conductance of leaves of Pyrus calleryana trees grown in the three pit types in 2010-2012 (n=5)
Figure 6: Evapotranspirational cooling of Pyrus calleryana trees grown in the three pit types in 2010-2012 (n=5)
Figure 7: Chlorophyll fluorescence in leaves of Pyrus calleryana trees grown in the three pit types in 2011-2012 (n=5)
Figure 8: Total chlorophyll content (a+b) of leaves of Pyrus calleryana trees grown in the three pit types in 2011-2012 (n=5)

Chapter 5
Figure 1: Differences in growth of P. calleryana grown in four different treatments. Annual growth rates (2010-12): a) height b) dbh c) crown diameter. Graphs show means ± standard error (n =5).
Figure 2: Differences in LAI of P. calleryana grown in 4 different treatments over three growing seasons (2010-12). Graph show means ± standard error (n =5).
Figure 3: Soil moisture content in 2011 and 2012 in the top 20 cm around the tree bases in four different treatments. Graph show means ± standard error (n =5).
Figure 4: Differences in leaf water potential of P. calleryana grown in 4 different treatments measured over 3 growing seasons (2010-12): a) mid day b) pre dawn. Graphs show means ± standard error (n =5).
Figure 5: Leaf physiological performance and evapotranspiration cooling capabilities of P. calleryana trees grown in different treatments over 3 growing seasons (2010-12): (a) stomatal conductance; (b) energy loss. Graphs show means ± standard error (n =5).
Figure 6: Chlorophyll analysis of P. calleryana trees grown in 4 different treatments measured over 2 growing seasons (2011-12): a) Chlorophyll a: b b) Chlorophyll fluorescence (Fv/Fm). Graphs show means ± standard error (n =5).
Figure 7: Sap flux density (Js) of trees grown in 4 different treatments between April 18 and September 30, 2012: a) daily sums of sap flux


density where each panel represents the mean of 2 trees measured for each treatment b) average sap flux density, where each panel represents the average of daily sap flux density of 2 trees over the growing season measured for each treatment. Error bars show the standard error (n = 143). There are missing values due to equipment failure.

Figure 8: Sap flow of trees grown in 4 different treatments between April 18 and September 30, 2012: a) daily sums of sap flow where each panel represents the mean of 2 trees measured for each treatment b) average sap flow, where each panel represents the average of daily sap flow of 2 trees over the growing season measured for each treatment. Error bars show the standard error (n = 143). There are missing values due to equipment failure.

Chapter 6

Figure 6.1: Comparison of water loss per unit area from eight young *P. calleryana* trees based on thermal dissipation sap flow method and leaf porometer at three times of 7 days in September, 2011.

Figure 6.2: Comparison of whole tree water loss from eight young *P. calleryana* trees based on thermal dissipation sap flow method and leaf porometer at three times of 7 days in September, 2011.

Figure 6.3: Mean ratio of whole tree water loss based on leaf porometer to sap flow measured on eight *P. calleryana* trees in September, 2011.

Figure 6.4: Energy loss calculated a) for five different tree species grown in different streets of Manchester, UK in May and July, 2011 (Chapter 2) b) from *P. calleryana* trees grown in three different growing conditions measured during July and August, 2010 in five different streets of Manchester, UK (Chapter 3) c) from *P. calleryana* trees grown in three different pit designs measured over the summers between 2010 and 2012 (Chapter 4) d) from *P. calleryana* trees grown in four different treatments measured over the summers between 2010 and 2012 (Chapter 5).

Figure 6.5: Water loss from grass in sun and shade, trees per unit canopy area and potential evapotranspiration rate (PET) in the Botanical Grounds of the University of Manchester in May, 2012.

Figure 6.6: Regression line between DBH increment and energy loss per unit area from *P. calleryana* trees grown in four different experiments a) Trees grown in cut-out pits in the pavements for six years (Chapter 2) b) trees grown in three different rooting conditions for six years (Chapter 3) c) trees grown in three different pit designs for three years (Chapter 4) d) trees grown in control and urbanized conditions inside the Botanical Grounds (Chapter 5).
List of Tables

Chapter 1

Table 1.1: General alterations in climate created by cities (after Landsberg, 1981) 20

Chapter 2

Table 1 Mean monthly temperature and rainfall data of 2011 and longer-term averages (1961-90) for the Northwest of England and North Wales between March and November 54
Table 2 Chlorophyll fluorescence of five different tree species grown on different streets in May, July and August, 2011 70
Table 3 Foliar nutrient status of five different tree species grown on different streets. Leaves were collected on August 15, 2010, 12 weeks after the full bloom 72

Chapter 3

Table-1: Mean monthly temperature and rainfall data for the Northwest of England and North Wales between February and November, 2010. 91
Table-2: Phenological observations of trees growing in the three different planting regimes. Phenological observations were carried out between mid of March, 2010 and mid of December, 2010. 99
Table-3: Foliar nutrient status of tree leaves growing in the three different planting regimes. Leaves were collected on August 12, 2010, 12 weeks after the full bloom. 102
Table - 4: Nutrient status of the three growth media. 103

Chapter 4

Table 1: Design of three types of pit used in the experiment 122
Table 2: Phenological observations on Pyrus calleryana trees grown in the three pit types. Observations were carried out between mid March and mid December, 2011 and 2012 and between mid September and mid December, 2010. 132
Table 3: Foliar nutrient status of Pyrus calleryana trees grown in the three pit types. Leaves were collected on August 15, 2011 and August 29, 2012 approximately 12/14 weeks after the full bloom. 138

Chapter 5

Table 1: Phenological observations of trees grown in the four different treatments. 167
Table 2: Foliar nutrient status of tree leaves grown in 4 different treatments. Leaves were collected on August 15, 2011 and August 29, 2012 approximately 12/14 weeks after the full bloom. 172
Abstract of a thesis by Mohammad Asrafur Rahman submitted to the University of Manchester for the degree of PhD in the Faculty of Life Sciences and entitled ‘Effects of Species and Rooting Conditions on the Growth and Cooling Performance of Urban Trees’. September, 2013

The urban heat island (UHI) is a problem that is likely to be exacerbated by ongoing climate change, but it is often claimed that urban trees can mitigate it and hence adapt our cities to climate change. Many researchers have attempted to quantify the cooling effects of trees using modelling approaches. However, the major disadvantage of most of the models is that they consider all vegetation to act as a single saturated layer and that their effect is merely proportional to its surface cover. Therefore, they fail to take into account potential differences between tree species and the effect of different environmental and growing conditions.

To address this issue four different studies were conducted in Manchester, UK from February, 2010 to December, 2012. The studies compared the growth and cooling abilities of several commonly planted urban tree species, and investigated a single species planted in a range of growing conditions: investigating the effect of urban soil compaction and aeration and also the effect of urbanization and simulated climate change in the rooting zone. Overall, our studies showed that species selection and growing conditions can substantially alter the evapotranspirational cooling provided by urban trees.

Fast growing species such as Pyrus calleryana, with their dense and wide canopy can provide cooling up to 2.2 kW tree\(^{-1}\), 3-4 times that of Sorbus arnoldiana, which have a thinner and narrower canopy and a moderate growth rate. P. calleryana was also investigated under three contrasting growth conditions: in cut-out pits in pavements; in grass verges; and in pits filled with Amsterdam soil. Trees in the less compacted Amsterdam soil had grown almost twice as fast as those in pavements and also had better leaf physiological performance. Together with a longer growing season, and better uptake of soil nutrients and moisture, trees grown in Amsterdam soil provided evapotranspirational cooling of up to 7kW, 5 times higher than those grown in pavements. Another experiment in which P. calleryana trees were planted in 3 standard planting techniques with non-compacted load bearing soils and with or without permeable slabs showed that optimum cooling is not only dependent on preventing soil compaction but also on ensuring that the covering materials are permeable to oxygen. Trees in the open pits provided up-to 1 kW of cooling, compared to around 350 and 650 W by the small and large covered pits respectively. Our final experiment showed that urbanization can increase tree growth by 20-30%; however, despite being under more water stressed conditions trees grown in simulated climate change plots had 40% higher sap flux density, and hence cooling potential. The study suggested that at least with P. calleryana, transpirational cooling benefit might be enhanced in places like Manchester with increased soil temperature in future, but potentially at the expense of photosynthesis and carbon gain.

Together these studies show that evaporative cooling of trees depends strongly on both species and growing conditions. If incorporated into regional and local energy exchange models our results can help us to quantify the magnitude and effectiveness of greenspaces in the city in adapting them to climate change.
**Declaration**

No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or institute of learning.

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Date:
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Thesis Organisation

This PhD thesis for examination at the University of Manchester has been submitted in the Alternative Format. This format allows the inclusion of chapters that are already published in peer-reviewed journals or in the format of a journal article. This means that the format of each chapter may differ slightly as the chapter is presented in the format of the journal of publication or intended publication. Therefore, reference lists are provided at the end of each research chapter whilst citations for the General Introduction and General Discussion chapters can be found at the end of the thesis. Research in Chapter 3 was carried out earlier than that in Chapter 2 and published before Chapter 2, but due to the flow of the thesis I have intentionally placed it later. I am the first author on all the chapters presented in this thesis. However, due to the collaborative nature of this research other authors have contributed to my work. The contribution of the authors for each of the chapters is outlined below.

Chapter 2:

I conducted the field and laboratory research and analysis for this paper. I wrote the paper with editing assistance from Dr Roland Ennos. Dr David Armson helped me during the field work. Dr Roland Ennos and I developed the initial research idea and the experimental design.
Chapter 3:

I conducted the field and laboratory research and analysis for this project. I wrote the paper with editing assistance from Dr Roland Ennos. Jonathan Smith helped me during the field work and Pete Stringer provided logistic support with initial field data from Red Rose Forest. Dr Roland Ennos and I developed the initial research idea and the experimental design.

Chapter 4:

I conducted the field and laboratory research and analysis for this project. I wrote the paper with editing assistance from Dr Roland Ennos. Pete Stringer provided logistic support for the project. I came up with the initial research idea and the co-authors and I developed the experimental design.

Chapter 5:

I conducted the field and laboratory research and analysis for this project. I wrote the paper with editing assistance from Dr Roland Ennos. Dr David Armson helped me in setting up the sap flow gauges in the field. Dr Roland Ennos and I developed the initial research idea and the experimental design.
Chapter 1

General Introduction
1.1 Climate change and urbanization

1.1.1 Climate change

Climate change has already passed the sphere of prediction and is now with us. Today climate change is one of the greatest global challenges and research is underway to establish the likely impacts on all aspects of the environment (Ray, 2008). As far as the UK is concerned, a warming of 3 – 5 °C during the summers in the 2080s is predicted even in medium emissions scenarios, with a probability level of 50% (Gill et al., 2007). Heat waves will also eventually become more common. A very hot August, such as in 1995 may occur once in every five years by the 2050s and three years in five by the 2080s under Medium-High emissions scenarios (UKCP09). Regional climate model simulations for Europe have warned that, under the IPCC A2 emissions scenario, by the end of the century one in every second summer could be as warm or warmer than the record breaking summer of 2003 (Schar et al., 2004). Seasonal precipitation patterns will also be altered, with drier summers and wetter winters (30 - 40% decrease in summer and 20 - 30% increase in winter rainfall in the 2080s for the medium emission scenarios, with a 50% probability level) (UKCP09).

However, climate change has been happening for billions of years as a result of internal variability within the climate systems and external factors (IPCC, 2001) yet because of the combined effect of greenhouse gases such as water vapour, carbon dioxide (CO₂) and methane in the atmosphere our planet is still habitable. Otherwise, the temperature of the Earth would be much lower than it is. The concern is the anthropogenic emissions of greenhouse gases which are threatening our sustainability. Since the industrial revolution, emissions of CO₂ have increased at a tremendous pace. Currently at 380 ppm, the
atmospheric CO$_2$ concentration is higher than at any time in the past 400,000 years (Petit et al., 1999) and has already caused a rise in global temperatures of 0.6 °C since the beginning of the twentieth century (Hulme et al., 2002). Therefore, there is an urgent need to strengthen adaptation and mitigation efforts at local levels.

Climate change obviously is a global issue; however, in terms of the impact on human society we have to think where most of the people are living. A survey carried out by the UN Department of Economic and Social Welfare revealed that the urban population of the world exceeded the rural population for the first time in 2007 and predicted that by 2030 more than 60% of the global population will be living in urban areas (McCarthy, 2009). Moreover, in developed countries the proportion of the urban population is already much higher than that of rural population. In Great Britain 90 per cent of the people live in urban areas (UNSD, 2009).

1.1.2 Urbanization

As a consequence of the ever increasing human population, our cities and towns are expanding worldwide and this is a continuous process. This urbanization process alters the landscape by replacing natural vegetation with impervious surfaces and artificial structures (McDonnell and Hahs, 2008) and thus contributes to the alteration of ecological processes (Whitford et al., 2001). The physical structure of the city, its artificial energy and pollution emissions, and the reaction of climatic elements with urban surfaces, have now become so large that urban areas can develop their own urban climate, which differs significantly from those of surrounding rural areas (Oke, 1978; Kuttler, 2008; Bridgman et al., 1995) (Table 1.1).
Table 1.1: General alterations in climate created by cities (after Landsberg, 1981)

<table>
<thead>
<tr>
<th>Climatic Element</th>
<th>Comparison with rural areas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td></td>
</tr>
<tr>
<td>Annual mean</td>
<td>0.5-3.0 °C higher</td>
</tr>
<tr>
<td>Winter minimum</td>
<td>2.5-4.0 °C higher</td>
</tr>
<tr>
<td>Summer maximum</td>
<td>1.0-3.0 °C higher</td>
</tr>
<tr>
<td>Relative humidity</td>
<td></td>
</tr>
<tr>
<td>Annual mean</td>
<td>6% lower</td>
</tr>
<tr>
<td>Winter</td>
<td>2% lower</td>
</tr>
<tr>
<td>Summer</td>
<td>8% lower</td>
</tr>
<tr>
<td>Cloudiness</td>
<td></td>
</tr>
<tr>
<td>Clouds</td>
<td>5-10% more</td>
</tr>
<tr>
<td>Fog, winter</td>
<td>100% more</td>
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<tr>
<td>Fog, summer</td>
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<tr>
<td>Total, horizontal surface</td>
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</tr>
<tr>
<td>Ultraviolet, winter</td>
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</tr>
<tr>
<td>Ultraviolet, summer</td>
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</tr>
<tr>
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<tr>
<td>Windspeed</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>20-30% lower</td>
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<tr>
<td>Extreme gusts</td>
<td>10-20% lower</td>
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<tr>
<td>Calms</td>
<td>5-20% lower</td>
</tr>
<tr>
<td>Precipitation</td>
<td></td>
</tr>
<tr>
<td>Amounts</td>
<td>5-10% more</td>
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<tr>
<td>Days with &lt;5 mm</td>
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</tr>
<tr>
<td>Thunderstorms</td>
<td>10-15% more</td>
</tr>
<tr>
<td>Snowfall, inner city</td>
<td>5-10% less</td>
</tr>
<tr>
<td>Snowfall, lee of city</td>
<td>10% more</td>
</tr>
</tbody>
</table>

Modified terrain such as concrete, asphalt and bricks, found in urban areas, absorb more heat during the day than the former vegetated surface and re-radiate it at night. This heat storage and re-emission leads to the creation of a phenomenon called “Urban Heat Islands” (Graves et al., 2001; Wilby, 2003). Absence of the energy absorbing process of evapotranspiration from natural vegetation further exacerbates this urban heat island effect.

1.1.3 The Urban heat island effect

One of the most apparent expressions of the urban microclimate is the urban heat island, as urban areas are warmer than the surrounding countryside by an average of 0.5 to 1.5 °C in temperate latitudes and up to 3 °C in tropical areas (Chen and Jim, 2008) (Fig. 1.1). Rosenfeld et al. (1995 & 1998) described the urban heat island phenomenon for
downtown Los Angeles over the period of 1882-1984. Until the 1930s the city of Los Angeles was cooled by 2 °C due to the higher amounts of irrigation and orchards. After the 1930s, however, the city warmed by 3 °C as paved surfaces replaced trees. Similarly, Carreiro and Tripler (2005) reported a temperature rise of 2 °C between 1974 and 1988 (1.3 °C per decade) due to urban expansion at Atlanta, Georgia.

Figure 1.1: A schematic diagram of urban heat island (adopted from Mayor of London, 2006).

This is mainly due to the modification of the landscape, where landscapes containing natural vegetation are converted into roads, buildings and car parks (Akbari, 2005). Removal of vegetation and installation of low albedo surfaces and street canyons modify the energy exchanges within the cities and towns and consequently increase the ambient air temperature (Gill et al., 2007). Fig. 1.2 shows that the reflection from the surface of urban areas is reduced compared with the rural areas and it has higher thermal storage. Urban areas with deep street canyons (high building height to street width ratio) can increase the amount of solar irradiance absorbed as well as reducing the escape of long wave radiation. This influences the radiation heat exchanges that take place between buildings and the atmosphere, and therefore can increase the UHI (Levermore and
Cheung, 2012). Heat flux models for Greater Manchester also demonstrated that buildings are the dominant emitter of waste heat energy, contributing some 60% of the total anthropogenic heat fluxes (Smith et al., 2009). Moreover, much less energy is lost by evaporation from surface water or living plants (Whitford et al., 2001). Consequently, the built environment absorbs more heat during the day and heats up the air more by convection, while also storing more absorbed heat that needs to be reradiated at night. Much of this radiation can be trapped in urban canyons, making the night-time urban heat island even stronger than that in the day time.

Figure 1.2: Diagram showing the comparison of energy exchange between rural landscapes (A) and an urban landscape (B) (adopted from Whitford et al., 2001).

Increased urban temperatures have an impact on the summer cooling demand in relation to the “intensity” of the heat island (Wilby, 2003). In conjunction with higher urban temperatures, summer heat waves are exacerbated, making the conditions very
unfavourable and causing massive health implications. The summer heat waves of 1976, 1995 and 2003 caused increased mortalities amongst the vulnerable members of the population (Laschewski and Jendritzky, 2002; Kosatsky, 2005). The heat wave of 2003, for example, has been estimated to have led to more than 15 000 additional deaths in the UK and France (Department of Health, 2008). More importantly, the risk of excessive deaths is greatest in large metropolitan areas that can suffer from urban heat island, such as London, Manchester and Birmingham (Defra, 2012). Thus there is an increasing need to evaluate strategies that may mitigate further increases in temperatures in urban areas and the associated negative impacts on human health (Bowler et al., 2010). The urban heat island effect may be both accentuated by climate change and exacerbate the impacts of heat waves (IPCC, 2001). Thus, it is apparent that the drivers of climate change do not act in isolation, but rather they act in conjunction with, and impact upon, each other (Gill et al., 2007).

However, this potential has not been fully explored. Additionally, climate change will impact on urban greenspaces themselves, and how this, in turn, may affect its functionality has not been widely investigated.

1.2 Vegetative cooling in urban areas

Urban greenspaces have a natural cooling effect upon the immediate surroundings. This cooling effect is principally due to evapotranspiration as well as solar shading and reflection. During a sunny day with clear skies, incoming radiation exceeds outgoing radiation and the surface absorbs net energy. The energy is distributed over three major categories of energy use, latent heat (LE), sensible heat (H) and ground heat flux (G). The amount of thermal energy or heat required to change the temperature of a substance
without water vapour content change is called sensible heat. Importantly there is a significant sensible heat (heat lost from the surface by convection) exchange between the warm urban air and the cooler leaves. On the other hand, the energy added or removed by a substance during a change of state without changing its temperature is called latent heat. A ratio of energy fluxes from one medium to another by sensible and latent heating respectively is expressed as the Bowen ratio $B$. It is calculated in the following way:

\[ B = \frac{Q_h}{Q_e} \]

where $Q_h$ is sensible heating and $Q_e$ is latent heating. When the value of $B$ is less than unity, a greater amount of available energy at the surface is passed to the atmosphere as latent heat than as sensible heat and vice-versa. In vegetated areas more heat is lost by evapotranspiration, with Bowen ratios varying from 0.4 to 0.8. Landscapes with sufficient vegetation cover use most of the radiant energy to evaporate water - mainly transpired through the plant leaves into the air – and so raise the air’s humidity. On the other hand, landscapes altered by human beings with less vegetation cover significantly reduce the evaporative surface. Therefore, most of the radiation energy is allocated to sensible heat transfer.
Figure 1.3: Types of energy balance

(A) Country sites – day time (B) Night time (C) Urban areas – day time (D) Night time (modified from Rouse, 1978).

Figure 1.3 shows typical forms of energy balance in country sites and urban areas. Positive net radiation of a large magnitude denoted by the long downward-directed arrow is shown in Fig. 1.3 (A). All other energy flows are directed away from the surface, evapotranspiration having the largest magnitude. Fig. 1.3 (B) shows that at night the net radiation is negative and small; all other energy flows toward the surface with sensible heat being larger than the latent heat flux. Water vapour condenses and falls in the form
of dew or fog, so the latent heat flux is released and for this reason the energy flow is positive towards the surface. In contrast, in the case of urban areas with very little evaporative surface almost all the net radiation is balanced by the sensible heat flux as shown in Fig. 1.3 (C) during the day time. At night as shown in Fig. 1.3 (D), net radiation is negative and depending on the thermal storage and long wave radiation, the length of the arrow will vary.

1.2.1 Evapotranspiration

A key process in reducing summer temperature in our cities is evapotranspiration, which describes the loss of water from a plant as a vapour into the atmosphere (Fig. 1.4). Water loss from a tree can be anywhere between 40-300 litres of water per day (Thomas, 2000). Transpired water from leaf surfaces can cool the air because the latent heat of vaporization from the ambient air is absorbed to convert liquid water into water vapour (Bowler et al., 2010). Water has a high specific heat and high heat of vaporization. The latent heat of vaporization is 2.45 kJ/g (Manning, 1997). Therefore, using the extra energy needed to break the hydrogen bonds of water and to release it as a gas molecule into the open air, trees lose a great deal of energy and cool down the surrounding atmosphere. The physical process of evaporation from soil surfaces associated with trees similarly contributes to air cooling, so the combination of evaporation from leaf surfaces and transpiration is called evapotranspiration. It is particularly important for mitigating the urban heat island effect as it acts like a natural air conditioning process. In favourable conditions, evapotranspiration can create ‘oases’ that are 2-8 °C cooler than their surroundings (Oke, 1987; Taha et al., 1991). In an intense oasis condition, the latent heat flux can be so large that the sensible heat flux becomes even negative, meaning that the
air above vegetation and over the dry surroundings must supply sensible heat to the vegetated area and the Bowen ratio becomes negative (Taha, 1997).

Figure 1.4: A schematic diagram showing tree transpiration process (Source: http://science.yourdictionary.com/transpiration)

In order to explain the natural patterns of evapotranspirational cooling efficiency of urban greenspaces it is crucial that we understand the controls over plant water relations and the consequences for tree growth of altered watering regimes. Water movement through a plant along a gradient occur in three ways: from high to low water potential (if transport occurs across a semi-permeable membrane), from high to low hydrostatic pressure (if no such membrane is involved), or from a high to a low partial water vapour pressure (Lambers et al., 1998). Water potential ($\psi$) is a measure of the chemical free energy of water. However, the low partial pressure of water vapour in the air compared with that inside leaves is considered to be the major driving force for water loss from leaves (Fig. 1.5).
1.2.2 Shading effect

In addition to evaporative cooling, shading from trees can act to cool the atmosphere by simply intercepting solar radiation and preventing the warming of the land surface and air (Oke, 1989). The radiation balance of an area is affected by the albedo of the surface which depends on the properties of that surface. Nevertheless, if the incoming solar radiation is reduced by the vegetation, the surface underneath gets less chance to heat up by absorbing energy. Direct shading by trees reduces incoming short wave radiation by 75-85%. The proportion of short wave radiation reflected is about 15-25% for green space and around 10-20% for tarmac and other man-made materials. Vegetation shading
itself does not reduce the air temperature, however; instead, air heats up less below the canopy as a result of the reduced amount of long wave solar radiation heat gain by the surfaces in the vegetation’s shade (Huang et al., 1987). This reduction in heat gain ultimately leads to less heat storage and therefore, less heat to be radiated from the ground. Therefore, shading only cools the people below the trees; it is evapotranspiration that actually reduces the temperature around trees in a city.

1.3 Quantifying the cooling effects of trees

Approach 1: Air temperature

To quantify the cooling effects of urban trees, many researchers have measured air temperatures within and outside a park or beneath or away from trees (Johansson and Emmanuel, 2006; Shashua-Bar et al., 2006; Yu and Hien, 2006). Based on a meta-analysis of their results, Bowler et al. (2010) concluded that the effects are usually small; parks had on average a daytime temperature only 0.94 °C cooler than the surrounding urban temperature. This is because warm air can be readily advected into parks and the cool air from parks advected into the surrounding streets. Thus, it seems impossible to relate local air temperatures to the overall urban heat island.

Approach 2: Surface temperature

Meteorologists studying the urban heat island need to understand the surface heat balance in order to make precise parameterisations for their meso-scale meteorological models (Martilli et al., 2002). Tree shade and evapotranspiration cool the surface temperature; therefore measuring surface temperature can help to predict the urban air temperature. A study in Basel, Switzerland, showed that at midday on a hot summer’s day, built surfaces, at 37–60 °C were 12–35 °C warmer than air, whereas the leaves of trees ranged
from 1 °C cooler to 4 °C warmer than air temperature (Leuzinger et al., 2010). Armson et al. (2012) monitored the surface temperatures of small plots composed of concrete and grass in the presence or absence of tree shading and reported that both surface and shade greatly affected surface temperatures. Grass can reduce maximum surface temperatures by up to 24 °C, while tree shade reduced them by up to 19 °C. The use of the surface temperatures in models is made more difficult because of the problem that leaf temperature is dependent on anatomical (leaf mass, size, shape, angle, reflectance), physical (incoming energy, air temperature, wind) and physiological (transpiration, stomatal conductance) factors (Monteith and Unsworth, 1990). Leaves absorb radiant energy in proportion to the surface exposed but heat at a rate that is inversely proportional to their heat capacity, thick leaves heat more slowly than thin ones (Ansari and Loomis, 1959). Since smaller leaves have thinner boundary layers, they also lose heat by convection faster, so small leaves tend to be cooler than large ones (Knoerr and Gay, 1965; Leuzinger et al., 2010).

**Approach 3: Measuring the Energy Exchange Balance**

Most cooling is provided by evapotranspiration, so a final approach is to measure water loss from trees. Calculating the mass flow of evapotranspiration (E) and its energy equivalent, the latent heat flow (LE), is a much better way of telling how much heat is going out into the atmosphere. A few researchers such as Thorpe (1978), Green (1993) and Barradas (2000) have attempted to calculate the energy partitioning of a single tree. Barradas (2000) measured the transpiration of a single tree hedgerow of *Fraxinus uhdei* using sap flow gauges and measured net radiation using eight radiometers around a tree to calculate the energy balance components of a single tree canopy in Mexico City. Barradas (2000) showed in his research that during the rainy season latent heat increased
in the day up to 184 W m\(^{-2}\) and dissipated 60\% of the net radiation. Similar results were shown by Thorpe (1978) and Green (1993) while calculating the radiation balance, transpiration rate and photosynthesis of an isolated tree. Researchers such as Suckling (1980) found \(Q_e \approx 0.65Q\) for a suburban lawn, similar to moist rural surfaces, for an environment in which advection was less likely.

However, experiments to quantify the amount of cooling provided by the trees in the urban environment are scarce given the difficulties in conducting well-replicated and experimental research on these topics (Bowler et al., 2010). Some studies have attempted to answers the uncertainties with modelling approaches (Chen and Jim, 2008; Jim and Chen, 2009). Researchers in the US have mainly studied the effect of tree shading in reducing the air-conditioning costs of building. Computer models using empirical data have shown that large trees planted on the south and west sides of buildings can cut air-conditioning costs by about 30\% (Nowak, 2000). Since vegetation increases both albedo and evaporative cooling and has lots of layers of leaves; it is difficult to represent how effective vegetation is at cooling in regional climate models (Ennos, 2010). Even when evapotranspiration is considered urban greenspaces are treated as one dimensional and cooling potentiality is calculated based on the Penmen-Monteith equation or measured using eddy-covariance analysis. For example, a study from the Lawrence Berkeley Laboratory by Huang et al. (1987) describes a model to estimate the cooling of air temperature due to urban greenspaces at a city scale using an equation for calculating potential evapotranspiration, and thereby computing the quantity of moisture being released by trees in a city. However, to calculate the localized effect of greenspaces in a neighbourhood this model cannot be used. Moreover, the use of potential evapotranspiration compromises on accuracy as this approach was originally developed
for crops and it only predicts the maximum evapotranspiration possible assuming ample supply of water and favourable conditions (Allen et al., 1998). In harsh growing conditions like those in a city these assumptions can be challenging most of the time.

### 1.4 Modelling the impact of vegetation in the urban cooling

A variety of different approaches have been taken to modelling urban temperatures. Following the pioneering work of Oke (1978) urban canopy energy budget modelling has received much attention (Terjung and Oourke, 1980; Sakakibara, 1996; Arnfield and Grimmond, 1998; Shashua-Bar and Hoffman, 2002, 2003; Gill et al., 2007). Some authors have focused on air temperature while many other focused on surface temperature (Whitford et al., 2001; Gill et al., 2007). Though surface and air temperature show some similar spatial and temporal patterns, this correspondence is not exact (Arnfield, 2003). Air temperature across an immediate landscape will be nearly identical due to the efficient mixing of the air (Brown and Gillespie, 1995), whereas surface temperatures vary more (Lowry, 1988).

To solve the problem of air temperature, Gill et al. (2007) used an energy exchange model to calculate the surface temperatures of vegetation, building and roads, using Greater Manchester as a case study area. Gill et al. (2007) used a simple 1d model developed and modified by Whitford et al. (2001) from the urban climate model of Tso et al. (1990, 1991). The model expressed the surface energy balance of an area in terms of its surface temperature, $T_0$ and showed output the surface and soil temperature ($T_0$ and $T_s$) as a function of time (Fig. 1.6).
It proceeds from the simple instantaneous energy balance equation (equation 1):

\[ R = H + LE + G + M \]  

(1)

R is the net radiation flux to the earth’s surface calculated as solar flux minus the long wave radiation to the atmosphere. H is the sensible heat flux due to convection and LE is the latent heat flux due to evaporation. Both remove energy through the boundary layer to its upper surface, level 2, which it is assumed has a constant temperature, wind speed and specific humidity. G is the conductive heat flux into the soil, through the intermediate layer, s, to the lower layer, b, which is assumed to have a constant temperature \( T_b \) or out of the material that constitutes the surface. This heat flux also increases with the surface temperature. M is the heat flux to storage in concrete and other built environment. This increases with the rate of temperature change, and with the area of built environment, and thus, mass of concrete (Whitford et al., 2001).
Simulation runs of the model showed that $G$ and $M$ are small component of the energy balance in an urban area with greenspaces. Behaviour of $G$ for simple facets has been described by Doll et al. (1985) and Anandakumar (1999) and can normally be evaluated using heat flux plates or by measuring time rates of temperature change if the heat capacity of the substrate is known (Arnfield, 2003). Moreover, since the convection heat depends both on $T_s$ and resistance to heat flow, we can solve any conductive or advective heat flux as storage heat flux ($S$) and rearrange the equation 1 as equation 2:

$$H = R - LE - S$$  \hspace{1cm} (2)

$H$ and $LE$ was calculated using the equation 3 and 4:

$$H = - K_h C_a (T_2 - T_0)$$  \hspace{1cm} (3)

$$LE = - K_v L (q_2 - q_0)$$  \hspace{1cm} (4)

where $C_a$ is the specific heat of air at a constant pressure, $L$ is the latent heat of evaporation, $T_2$ is the temperature at level 2, and $q_0$ and $q_2$ are the specific humidities at levels 0 and 2. The coefficients of eddy diffusivity of heat, $K_h$, and of water vapour, $K_v$, was solved using meteorological parameters such as air density, wind velocity and air temperature. Now if one can empirically determine the evapotranspiration rate it is much easier to solve sensible heat flux. The major disadvantage in most of the models (Grimmond and Oke, 1999; Shashua-Bar and Hoffman, 2000; Whitford et al., 2001; Gill et al., 2007) is that it becomes difficult to explain the processes involved in more detail. Urban climatologists such as Grimmond and Oke (1999) have presented an evapotranspiration-interception model for urban areas with a Penman-approach using a single integrated surface resistance for the whole system. Generally, Bowen ratio-energy balance (BREB) or eddy covariance methods are used to determine heat fluxes of different areas (Barradas, 2000). A main characteristic in urban areas is the difference in
land use which affects the uptake or release of energy by sensible and latent heat fluxes (Oke et al., 1992).

Once we know the energy exchange balance for a single unit of vegetation this will eventually help to model the energy exchange model of a city with much more confidence. To input H and LE parameters in the model simulation run, Gill et al. (2007) also used few assumptions which include a lot of uncertainties and limitations. The major limitations of this model include: 1. All greenspaces were treated as one single saturated layer of vegetation; the three dimensional properties of tree canopy have been ignored. 2. It did not consider the shading effect. 3. It did not consider the growth conditions or the potential species differences. Moreover, estimates on cooling the air temperature based on the shade effect alone would lead to overestimation, and those based on the evapotranspiration alone to underestimation (Shashua-Bar and Hoffman, 2002).

However, understanding the behaviour of individual surfaces is a prerequisite before we can begin to understand the urban environment as a whole. While comparing 33 international urban energy models Grimmond et al. (2010) showed that they have the best overall capability to model net all-wave radiation but the least capability to model latent heat flux. Therefore instead we need to use a small scale approach, taking into consideration the energy balance of individual trees and then scale up to a larger area. The detailed energy balance of an individual tree will depend on its species, and on its response to its growing conditions. If we know how all the trees behave this information can be incorporated into climate models in combination with geographical information systems. These models could then be a powerful tool to suggest how greenspaces can be an effective means to adapt urban areas to the consequences of climate change through the provision of cooler microclimates.
1.5 Comparing the cooling efficiency of trees

1.5.1 Species differences

To model the energy balance of a city using small scale elements we need to understand the effect of species difference and environmental gradients since dissipation of the heat load by transpirational cooling may vary with the climate, tree species and environmental conditions (Oke, 1989; Shashua-Bar and Hoffman, 2000; Pataki and Oren, 2003; Bovard et al., 2005; Tang et al., 2006; Bowden and Bauerle, 2008; Leuzinger et al., 2010; Peters et al., 2010). Transpiration rates of species from hot dry habitats are usually low as they conserve water by closing their stomata and hence should have a smaller effect on the air temperature than trees from cooler, wetter habitats (Hemsely and Poole, 2004). Despite the long term interest in the water use of urban trees for urban forestry applications, and, more recently, from the perspective of urban ecology and coupled human–ecological interactions, there are few datasets of transpiration rates of urban trees and forests in the field (Pataki et al., 2011). Total evapotranspiration rates from meteorological measurements (Kalanda et al., 1980; Grimmond and Oke, 1999; Christen and Vogt, 2004) or models (Grimmond and Oke, 1991; Berthier et al., 2006; Mitchell et al., 2008) provide little information about the direct plant transpiration rate or differences between species. The evapotranspiration (ET) of different tree species in urban landscape could theoretically be calculated by incorporating a crop factor $K_C$ into the Penman-Monteith equation (Allen et al., 1998)

$$ET = ET_0 \times K_C$$

The reference evapotranspiration ($ET_0$) is calculated from continuous measurements from a layer of well-watered grass growing in a large field, rendering boundary effects
negligible. \( K_c \) is available from the tables of crop factors are given by Allen et al. (1998); it tends to be around or less than 1 for most crop plants but can exceed 1 for some orchard trees (Ennos, 2011). Since the original equation was meant for studies of the irrigation requirements of agricultural crops, however, estimation of evapotranspiration of different tree species in the urban landscape might have limitations. Importantly, generally evapotranspiration of droughted crops is reduced by a factor proportional to the matric potential of the soil (Rowell, 1994; Allen et al., 1998) and this may differ significantly in urban trees. Moreover, the three-dimensional shapes of trees are ignored. Isolated street trees will tend to have significantly higher evapotranspiration per unit crown area than a large homogenous crop field since trees protrude out of the boundary layer into the wind; this increased drying is known as the clothes-line effect (Allen et al., 1998).

Kjelgren and Clark (1993) studied 10-year old sweet gum (Liquidambar styraciflua L.) trees planted in a partially vegetated urban park and in an urban plaza in Seattle, Washington for two years. They calculated transpiration rate \( (g \, m^{-2} \, s^{-1}) \) as the product of vapour pressure deficit \( (VPD) \), divided by barometric pressure, and stomatal conductance, and approximated whole-tree transpiration \( (g \, s^{-1}) \) by multiplying by sunlit-crown area. They showed that radiant energy partitioned by paved surfaces into higher surface temperature and VPD will increase transpiration rates if soil moisture is not limiting. In a separate experiment Kjelgren and Montague (1998) and Montague et al. (2004) measured leaf-level gas exchange and water loss from containerized seedlings of Pyrus calleryana, Fraxinus pennsylvanica, Accer platanoides, Malus ionensis, Salix matsudana and Platanus occidentalis by taking measurements of their mass over vegetative and non-vegetative surfaces. They reported that due to greater longwave
radiation interception, leaves of *F. pennsylvanica*, *A. platanoides*, *M. ionensis*, *S. matsudana* had greater leaf temperature and leaf-to-air vapour difference than leaves over vegetative surface. As a result, trees over non-vegetative surfaces generally had lower stomatal conductance and water loss than trees over turf. However, *P. calleryana* and *P. occidentalis* showed almost one third more water loss when grown over asphalt than turf.

Bush et al. (2008) measured sap flux rates in mature trees of several species in Salt Lake City, Utah, USA, and found differences in stomatal responses to vapour pressure deficit in species of contrasting wood anatomy. Pataki et al. (2011) showed that species composition is a more important driver of urban forest transpiration than meteorological variables in Los Angeles, USA. Using sap flow gauges on mature urban trees they showed very large species differences in transpiration (more than 50 fold) with estimates ranging from 3.2 kg tree\(^{-1}\) d\(^{-1}\) in *Pinus canariensis* to 176.9 kg tree\(^{-1}\) d\(^{-1}\) in *Platanus hybrida* in the month of August. However, calculating the latent heat flux in terms of per unit canopy area of individual trees from existing studies is really challenging. The majority of the studies have reported water loss from trees using sap flow analysis since this method is seen as being more reliable compared to measurements based on the leaf transpiration rate, although, Ansley et al. (1994) reported that the two methods are comparable, with considerable variation between methods during peak transpiration rates. The results of sap flow analysis are presented in terms of sap wood area, which is difficult to convert into per unit canopy area without knowing the canopy area of that particular tree. Even if we know the whole tree transpiration rate and canopy area, solving the peak transpiration rate of that tree is usually difficult since transpiration rates are usually presented per day or over the season, not continuously. Because of the problem of scaling up the leaf transpiration based on porometry, studies calculating the
canopy transpiration rate using this method are scarce. Motzer et al. (2005) investigated tree water relations of five different trees species namely: *Ruagea pubescens; Psychotria brachiata; Trichilia guianensis; Naucleopsis sp.; Hedyosmum anisodorum* in a lower tropical montane rain forest at 1950 –1975 m above sea level in southern Ecuador. While calculating the leaf transpiration rate they replaced leaf boundary layer resistance ($g_b$) by an expression introduced by McDermitt (1990):

$$g_b = C (u/d)^{0.5}$$

where $u$ is wind speed (m s$^{-1}$), $d$ is mean leaf extension (m) and $C$ is a constant ($\approx 0.24$ mmol m$^{-2}$).

Motzer et al. (2005) reported leaf transpiration rates ranging between 0.52 and 1.60 mmol m$^{-2}$ s$^{-1}$ which can be converted into latent heat flux between 23 W m$^{-2}$ and 71 W m$^{-2}$.

Therefore, it will be very important to investigate species differences in evapotranspiration and take them into consideration when modelling the energy exchange balance of a city. By integrating species-specific benefits into the process of urban design, urban planners should be able to select appropriate tree species to maximize specific ecosystem services (Xie et al., 2011) and urban climatologist will be able to model the cooling effect of different trees while having to make fewer assumptions.
1.5.2 Growth conditions

In order to determine how much cooling urban greenspaces can provide, it is also crucial to understand what controls tree growth, and the consequences of planting trees in the harsh ecological conditions of the urban environment and the tree planting techniques used. The most limiting factor in the growth of urban trees surrounded by pavement is usually the lack of suitable soil for root growth (Smiley et al., 2006) (Fig. 1.7). This is mainly due to the soil compaction from vehicular and pedestrian traffic. The urbanization process itself also involves soil being compacted to ensure its load-bearing ability (Bartens et al., 2009) ultimately leading to low porosity, restricted aeration, sluggish infiltration and drainage and inadequate storage capacity for plant-available moisture (Whitlow et al., 1992). In addition to soil moisture availability in the rooting zone (Rhoades and Stipes, 1999), nutrient deficiency and contamination by pollutants (Jim, 1998) are also major determinants of tree growth and physiological performance in urban growing conditions. All these factors lead to poor growth in urban street trees in comparison to trees in park or natural settings (Kjelgren and Clark, 1993; Close et al., 1996 a; Close et al., 1996 b; Iakovoglou et al., 2001; Leuzinger et al., 2010). There is some empirical data on plant responses in urban conditions compared to trees grown either in natural conditions or in special structural soil (Kjelgren and Clark, 1992; Close et al., 1996 a; Close et al., 1996 b; Rhoades and Stipes, 1999; Grabosky et al., 2009). Close et al. (1996 a) and Close et al. (1996 b) also compared the growth and phenology of sugar maple (Acer saccharum) trees growing in a forest and in tree lawns on urban streets and reported that trees growing in parks or forests had 50% higher growth increment and had double the stomatal conductance of trees grown in the streets. Cermak et al. (2000) measured the sap flux of urban Acer campestre trees and attributed variability between the trees to differences in root area. Another recent study also showed
a reduced transpiration rate (55% for oak and 70% for ash) compared to the optimum transpiration under slow infiltrated soil inside a greenhouse (Bartens et al., 2009).

Along with greater soil volume, better aeration and drainage is also very important for better root growth of urban trees especially for those planted in streets or other paved areas for optimum size and cooling potentiality. To overcome the problem of soil compaction and increase the load bearing capacity of the soil, authors such as Kristoffersen (1998) have proposed a load-bearing growing medium under sealed pavement to carry light traffic. However, studies have shown that even permeable paving surface might reduce gas diffusivity by a factor of up to 10 compared to planting pits without sealing (Weltecke and Gaertig, 2012). There is little information on the
impact of these load bearing soils or the impact of sealed pavements on tree growth and physiology.

1.5.3 Climate change feedback

As well as the lack of information about the effect of rooting conditions on tree growth, there is also little information about the likely impact of climate change on urban greenspaces themselves and how this, in turn, may affect its functionality. Climate change is already impacting plant range and abundance. Gill et al. (2013) modelled the likely impact of climate change on the droughting of amenity grass in Greater Manchester, UK. The results showed a reduced evapotranspiration for 3–5 months by the 2080s, and evapotranspiration reducing by over a half for 1–2 months, in an average year. Gill et al. (2013) also reported that such changes could increase surface temperature by up to 15 °C in areas where grass accounts for a large proportion of the surface cover. However, due to their deeper root systems, trees can access to more water than grass and so should be less affected by short periods of drought (Thomas et al., 2006; Bucci et al., 2008; Chen et al., 2011). However, along with the soil compaction and soil aeration, the effects of the anticipated climate change on the soil-plant rhizosphere, such as summer drought or increased temperature, might cause serious damage to the growth and evapotranspiration cooling properties of trees. The predicted warmer wetter winters and hotter drier summers, with consequent increase in air and soil temperature at least in the UK, will further complicate the ecosystem services provided by urban trees (Gill et al., 2008). Due to the lack of evapotranspirational cooling, urban surfaces already show temperatures up to 4 °C higher at 10 cm depth than in forested sites nearby (Johnson et al., 1975); together with the anticipated climate change, this will definitely have an effect on the growth and evapotranspirational cooling properties of urban trees. So far, very few
studies have investigated the effects of climate change on trees in urban environments. Dendrochronological studies have shown an extended growth period of trees in warmer cities compared to rural areas (Roetzer et al., 2000; White et al., 2002). However, where drought stress is important, a longer growing season may mean only that plant respiration exceeds photosynthesis for a longer time, which would result in reduced growth (Aber et al., 2001). In the long term a 20% reduction in stomatal conductance at double CO$_2$ (based on 1961-90 level) is predicted (Aber et al., 2001) although some modelling studies have shown that increased CO$_2$ may remove the water stress and thus increase productivity (the so-called fertilization effect). In addition, researchers such as Infante et al. (2001); Martinez-Vilalta et al. (2003) have also investigated the effects of seasonality on the transpiration of Mediterranean evergreen forests and reported that peak transpiration occurred in the late spring with a strong decrease during the summer drought when cooling will be at a premium.

Moreover, summer drought with winter flooding as predicted by the global climate models (GCMs) might cause damage to the growth and evapotranspirational cooling properties of urban trees in the following years. In some cases, even short periods of inundation can affect plant biology dramatically (Russel, 1977; Whitlow and Harris, 1979). Plants exposed to soil flooding may face low oxygen concentration in the soil. This situation may lead to a lower level of water-channel proteins and hence a lower hydraulic conductance (Lambers et al., 1998). Researchers such as Montague et al. (2004) and Hagishima et al. (2007) have investigated the water use of potted plants in varying urban landscaping compositions. However, the growth and the energy budgets of potted plants are quite different from those in natural settings. Carrying out experiments to investigate the actual responses of trees in simulated changed climatic conditions
could be highly illuminating. Besides, long term monitoring of sap flow might also help to resolve some of the uncertainties in this field especially regarding the effect on the evapotranspirational cooling potentiality of urban trees.

1.6 Aims, objectives and chapters

The overall aim of this project is to quantify the amount of evaporative cooling that urban trees provide and also to quantify the effects of the built environment and future climate change on urban trees. However, this must be broken down into smaller objectives to determine the role of trees and the effects of their potential threats. In particular we had three main research objectives:

1. To investigate the relative growth and cooling performance of different tree species;
2. To investigate the effects of growth conditions on the growth and cooling performance of a single species of tree; and
3. To investigate the likely effects of climate change.

The urban landscape of Manchester, UK was chosen as a location to conduct this research, most of all because of the logistical support from the university and its partners such as the Sustainable Consumption Institute, University of Manchester (SCI), Red Rose Forest, and Manchester City Council. Moreover, although Manchester currently has few problems with excessive heat, it is a good example of a mega city with a temperate maritime climate, which does show a pronounced urban heat island effect of 3 – 5 °C (Smith et al., 2011). Issues relating to heat are also likely to become more of a concern in future changed climate scenarios (UKCP09). The tree species Pyrus calleryana was selected for consecutive studies since it is one of the most commonly planted urban tree
species in Manchester, and we found it to be one of the most tolerant to urban conditions, while also showing the highest cooling potential among the tree species surveyed.

To achieve our research objectives, we compared the growth rate; stomatal conductivity; leaf chlorophyll and nutrient status, and leaf water potential of different urban trees species, growing in different below-ground conditions and under current conditions and simulated climate change. The project was split into four different studies that separately investigated these factors.

The first study (Chapter 2) investigated the growth and cooling effectiveness of five commonly planted urban tree species: *Sorbus arnoldiana; Crataegus laevigata; Malus ‘Rudolph’; Pyrus calleryana* and *Prunus ‘Umineko* (Appendix 1). The trees had been growing for the previous six years in eight different streets of South Manchester under the same growing conditions. In conjunction with a sister study (Armson et al., 2013), which investigated the area and depth of shade provided by the same trees to determine the shading benefits, these studies offer a broad comparison of the climatic benefits of the five species, and give an indication of which factors are important when selecting an ideal urban street tree.

Following this, a series of other experiments was carried out to understand the effect of growing conditions and the potential feedback due to simulated climate change conditions. In particular, the second study (Chapter 3) investigated the effect of different planting regimes on the growth and cooling performance of *Pyrus calleryana* trees that had been growing for five to six years in five different streets of south Manchester (Appendix 2). The trees had been planted in three contrasting ways: in normal soil within
the pavement; in grass verges; and in Amsterdam soil within the pavement. The third
study (Chapter 4) compared three further standard planting techniques commonly used to
plant trees in Manchester (Appendices 3.1 & 3.2). *Pyrus calleryana* trees were planted in
smaller or bigger cut-out pits with contrasting topsoil, compaction reduction mechanisms
and sealing. Their growth, leaf chlorophyll analysis, leaf water potential, stomatal
conductance and nutrient status were then assessed for three growing seasons between
April, 2010 and December, 2012.

Finally, the sensitivity to growth and cooling potentiality of urban trees to climate change
impacts was assessed (Chapter 5). This study was designed to separately determine the
effects of urbanization and anticipated climate change in the soil-root rhizosphere
(Appendix 4). To do this, *Pyrus calleryana* trees were grown in a factorial experiment
with or without compacted soil and paving, and with or without soil heating and altered
rainfall input. Plants were grown and monitored between April, 2010 and December,
2012 in the Botanical Grounds of the University of Manchester, UK. Their growth, leaf
chlorophyll status, leaf water potential, stomatal conductance, soil moisture and nutrient
status were assessed along with soil and air temperature, wind speed, rainfall
measurements. Sap flow measurements were also carried out in eight trees (two from
each treatment) between April and September, 2012.

This work is then drawn together in a general discussion (Chapter 6) in which these
individual studies are integrated to give conclusions about the growth, stress tolerance
and cooling potentiality of urban tree species and their feedback to anticipated climate
change conditions. The possible development of regional and local energy exchange
models considering each of these individual components are also discussed. Finally, a
summary of the main research findings, and an evaluation of the research process are given and recommendations are made for further research and for the role of trees in urban environmental management.
Chapter 2

A comparison of the growth and cooling effectiveness of five commonly planted urban tree species

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A comparison of the growth and cooling effectiveness of five commonly planted urban tree species

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Abstract

It is often claimed that evapotranspiration from urban trees can mitigate the urban heat island and adapt our cities to climate change; however, the relative effectiveness of different tree species has rarely been investigated. The current study addressed this shortcoming by comparing the growth and physiology of five commonly planted tree species: *Sorbus arnoldiana*, *Crataegus laevigata*, *Malus* ‘Rudolph’, *Pyrus calleryana* and *Prunus* ‘Umineko’. The study was conducted between March and November, 2011 in eight different streets of Manchester, UK where trees had been growing for 6 years in the same growing conditions. The study showed that evapotranspirational cooling is closely related to the growth and stress tolerance of tree species. Of the species tested, *Prunus* ‘Umineko’ and *P. calleryana* were the fastest growing and *Malus* ‘Rudolph’ was the slowest growing. In general faster growing species showed higher leaf area index (LAI) and higher stomatal conductivity and so provided more cooling. However, *Prunus* ‘Umineko’ had surprisingly low cooling and showed signs of drought stress. *P. calleryana* showed up to 100% higher stomatal conductance than the other tree species. Combining the higher LAI and wider canopy, *P. calleryana* and *C. laevigata* provided cooling up to 2.2 kW tree⁻¹, 3 to 4 times of cooling to that of *Prunus* ‘Umineko’ and *S. arnoldiana* and showed no signs of drought stress. *Malus* ‘Rudolph’ showed stress tolerance but provided low cooling. *Prunus* ‘Umineko’ and *S. arnoldiana* with their thin and sparse canopy provided low cooling and showed susceptibility to urban stress.

Keywords: evapotranspiration; growth; cooling effectiveness; stress tolerance; leaf area index (LAI); stomatal conductivity.
1. Introduction

An understanding of how green spaces can reduce the urban heat island and so adapt our cities to climate change is well developed (James et al. 2009; Shashua-Bar and Hoffman 2000; McPherson et al. 1997; Leuzinger et al. 2010; Oke 1989; Peters et al. 2010). Trees cool down the local urban canopy and boundary layer through evapotranspiration (Rahman et al. 2011) and they also reduce the heat storage of surface structures by shading them (Armson et al. 2012; Nowak 2000). However, many questions remain unanswered about their effectiveness, particularly regarding the magnitude of evapotranspirational cooling and its effects on the urban microclimate (Souch and Souch 1993). Researchers such as Miller (1980), Kjelgren and Montague (1998) and Rahman et al. (2011) have all shown that street trees can transpire more per unit canopy area than a patch of vegetation or a group of trees in natural habitats because high advection increases the rate of evaporation. However, dissipation of the heat load by transpirational cooling may vary with climate, tree species and environmental conditions (Bovard et al. 2005; Bowden and Bauerle 2008; Catovsky et al. 2002; Givnish 2002; Pataki and Oren 2003; Tang et al. 2006; Wullschleger et al. 2001; Oke 1989; Shashua-Bar and Hoffman 2000; Peters et al. 2010). Transpiration rates of species from hot dry habitats may be low as they conserve water by closing their stomata and hence should have a smaller effect on the air temperature than trees from cooler, wetter habitats.

In a previous study we have also shown that tree performance can be improved by growing trees in non-compacted urban soils (Rahman et al. 2011). On the other hand, harsh urban growing conditions may only allow a limited number of tolerant tree species to be planted in our streets. Diversification of species is also complicated by our limited understanding of how different urban tree species differ in their water use (Peters et al.
Recent studies in desert environment have shown that different tree species have substantially different cooling properties (Saaroni et al. 2004; Potchter et al. 2008). While comparing native desert species with tropical and sub-tropical tree species, Potchter et al. (2008) showed that sub-tropical trees can cool down their surrounding atmosphere 4 °C more than the desert species. For this reason Pataki et al. (2011) reported that species composition is the most important driver of spatial variability in urban forest transpiration. Thus urban tree planting programmes need to be planned thoroughly, since unsuitable species selection certainly involves high costs (Leuzinger et al. 2010). At present trees in urban streets are mainly planted based on their aesthetic values and stress resistance. The European tree survey revealed that although a wide range of tree species are used in Central and North-West Europe, three to five genera account for 50–70% of all street trees planted (Pauleit 2003). In the UK a new national survey of England’s urban trees revealed that six species comprise around 37% of all trees and shrubs planted in the cities. They were Leyland cypress (x Cuprocyparis leylandii) (12.3% of all trees and shrubs), hawthorn (Crataegus spp.) (6.3%), sycamore (Acer pseudoplatanus) (5.7%), silver birch (Betula pendula) (4.6%), common ash (Fraxinus excelsior) (4.1%) and privet (Ligustrum spp.) (3.7%). Other common species included Lawson cypress, pedunculate oak, apples (Malus spp.), Japanese cherry, holly, rowan and beech (Britt and Johnston 2008). The majority of trees currently being planted in urban streets, however, are small members of the family Rosaceae. Lack of knowledge regarding the growth and physiological responses of such tree species in the urban environment is holding back the planting of trees for environmental purposes. Comparing the performance and stress tolerance of different tree species can therefore inform urban planning decisions. By integrating species-specific benefits into the process of urban
design, urban planners will be able to select appropriate tree species to maximize specific ecosystem services (Xie et al. 2011).

In order to quantify the transpirational cooling benefits provided by a tree species, it is very important to measure both its growth and physiological variables. Therefore, researchers have attempted to simplify the complexities over the years to answer different questions related to urban tree growth and functionality. Measures of growth include terminal shoot growth, diameter at breast height (DBH), crown spread, and leaf area index (LAI) (Close et al. 1996; Larsen and Kristoffersen 2002; Yang et al. 2005; Souch and Souch 1993). To quantify stress, authors such as Kent et al. (2004), Percival et al. (2006) and Ow et al. (2011) have measured leaf chlorophyll concentration, chlorophyll fluorescence, and water potential, while Kopinga and Van Den Burg (1995) and Close et al. (1996) have measured foliar nutrient concentrations. To quantify evaporative cooling Pataki et al. (2011) and Peters et al. (2011) have made sap flow measurements. Since impervious surface and compacted soil also alter local hydrological process, which are an important control on transpiration, water potential, stomatal conductivity and gas exchange have also commonly been used to assess the water status and physiological responses of plants under water stress condition (Pereira et al. 1986; White et al. 2000; Lawlor 2002; Rahman et al. 2011). The aim of this study was to compare the performance, stress tolerance and cooling effectiveness of five commonly planted UK street tree species, which had been planted six years previously under similar soil conditions. To do this, we measured aspects of their growth, their stress levels, and their transpiration on hot summers’ days. The study was carried out in conjunction with a study by Armson et al. (in press) which investigated the area and depth of shade provided by the same trees to determine the shading benefits. Together these two studies
aim to give a broad comparison of the climatic benefits of the five species, and give an indication of factors important for selecting a good street tree.

2. Methods

2.1 Site and species selection

The study was carried out in Greater Manchester, UK, which is a large conurbation (population 2.5 m) located in the North West of England (Armson et al. 2012). It has a temperate maritime climate with a mean annual temperature of 9.8 °C and annual precipitation of 806.6 mm (http://www.metoffice.gov.uk/climate/uk/averages/19712000/sites/manchester_airport.html). The study was carried out over a period of 9 months between March and November, 2011; a period characterised by a cold winter up to the end of March, a dry and very warm spring, a cool summer and a very warm autumn. Monthly weather data from the Met office (http://www.Metoffice.gov.uk/climate/uk/datasets/) for the Northwest of England and North Wales are shown in Table 1.

**Table 1** Mean monthly temperature and rainfall data of 2011 and longer-term averages (1961-90) for the Northwest of England and North Wales between March and November

<table>
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<th>March</th>
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<td>2011</td>
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<td>1961-90</td>
<td>4.7</td>
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<td><strong>Mean rainfall (mm)</strong></td>
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<td>2011</td>
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<td>1961-90</td>
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<td>110.1</td>
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We investigated tree growth and soil shear strength in 95 trees of five different species which met certain criteria for tree morphological measurements. There were 15 *Sorbus arnoldiana* Schouten, 27 *Crataegus laevigata* Pauls Scarlet, 14 *Malus* ‘Rudolph’, 26 *Pyrus calleryana* Chanticleer and 13 *Prunus* ‘Umineko’ and all were planted in 2005-06 at the age of 4/5 years. Next we sub sampled 9 *Malus* ‘Rudolph’, 12 *C. laevigata* and 10 trees each from *S. arnoldiana*, *P. calleryana*, *Prunus* ‘Umineko’ for stress tolerance and physiological measurements. *Pyrus calleryana* is native to eastern and southern China; however, it is widely cultivated in North America (Vincent 2005) and has become very popular in street planting in the UK. *Crataegus laevigata* is native to western and central Europe and is also a popular choice for urban planting in the UK (http://www.brc.ac.uk/plantatlas/). The trees of the genera *Prunus*, *Sorbus*, and *Malus* are widely distributed throughout the Northern Hemisphere (http://plantshq.aeronsoftware.com/). *Prunus* ‘Umineko’ is a cross between *Prunus incise* and *Prunus speciosa*; *Sorbus arnoldiana* Schouten is a *Sorbus aucuparia* clone very popular for street planting, especially in London, and *Malus* ‘Rudolph’ is a Canadian clone developed in the 1950s, which has become popular all over the European temperate region as an urban tree.

The criteria required the trees to be planted in 1.5 m$^2$ cut-out pits in the pavement; to be of uniform age; to have been growing under the same conditions for the same time span; and for the initial size and planting conditions of the trees to have been recorded. These criteria were met on eight streets, all of which were located in the Whalley Range and Levenshulme area of South Manchester (Fig. 1).
Among the streets, Manely Road (53°26´49˝N, 2°15´39˝W) had 23 trees, Victoria Road (53°27´05˝N, 2°15´33˝W) had 11 trees, Palmerston Avenue (53°26´51˝N, 2°15´44˝W) had 9 trees, Granville Avenue (53°26´50˝N, 2°15´55˝W) had 5 trees, Cringle Road (53°26´10˝N, 2°10´52˝W) had 19 trees, Beech range (53°26´35˝N, 2°11´48˝W) had 9 trees, Victoria Avenue (53°26´27˝N, 2°11´41˝W) had 7 trees, and Thorncliffe Grove (53°26´36˝N, 2°10´51˝W) had 12 trees. Trees were planted by the Red Rose Forest under the ‘Green Street Project’. They used container grown plants which were watered by the residents during the establishment period (the first 2 years). The City Council is responsible for long term management such as formative pruning and removing guards and stakes when the trees are at an appropriate size. All the street trees were in residential areas and were planted in the cut-out pits of pavements and near the boundary line between two houses. Trees were around 7 – 10 m apart from each other and planted next to the kerb. The minimum distance to the boundary walls or fences was 2 m. All the studied trees were free of any visual decay symptoms, damage or dieback.
2.2 Tree growth and soil shear strength

Average tree height, DBH (Diameter at Breast Height – 1.37 m) and canopy spread at the time of planting were collected from the nursery who supplied those trees for planting in the above mentioned streets. To compare the growth increment of trees, the total height of each tree was measured using a Suunto Clinometer, and bole height, DBH, and canopy spreads in four directions were measured using a measuring tape in March and April, 2011. To obtain the mechanical properties of the soil, the shear strength was also measured at the same time using a shear vane attached to a torque meter (model RS 575-633). The vane was pressed into the soil to a depth of 50 mm and slowly rotated measuring the shear torque required. This was done at five different positions in each exposed tree pit. This gave a measurement of soil shear strength, which is related to compaction (Zhang et al. 2001).

2.3 Total stored CO₂ calculation

Few studies have estimated CO₂ storage in urban trees. Authors such as Nowak (1994) have estimated biomass using allometric equations mostly based on forest grown tree species. Reid and Stephen (2001) instead estimated the volumes of trees grown in the farms using the formula for a cone ($\pi r^2h/3$). We choose the formula for a cylinder to estimate green volume of each tree:

Green volume = $\pi r^2h$  

(1)

Where r is the radius (DBH/2), and h is the total height of the tree. Since this was intended for estimation of C sequestration rate and trees were not meant for timber production, total height was considered instead of merchantable height. We assumed that the total volume of all the branches in the canopy was equivalent to the cylindrical volume of the main stem. Additionally, as the trees were very young and mostly
cylindrical in shape, a taper function was not added into the formula (equation 1). Drywood (DW) biomass was then determined by multiplying the dry wood density of each tree species. We assumed a density of 0.70 g/cm³ for *C. laevigata* and 0.60 g/cm³ for the other four tree species (Zanne et al. 2009). Total DW biomass including the below-ground biomass was estimated by multiplying the above ground DW biomass by 1.28 (Husch et al. 1982; Wenger 1984). Total DW biomass was then multiplied by 0.50 (Lieth 1963; Whittaker and Likens 1973) to give the amount of carbon (C) stored by the trees. Finally the stored C was converted into the mass of CO₂ by multiplying by the constant 3.67, the molecular weight of carbon dioxide divided by that of carbon.

2.4 Crown, Soil and Physiological measurements

Crown, soil and physiological measurements were taken twice over the summer for each tree, between 11.30 and 16.30 h BST (British Summer Time) on warm sunny days. Because of unusually cool and cloudy weather during the summer and large sample size; however, measurements on all the trees could not be carried out on a single day. Trees were therefore measured on May 25 and June 03 (henceforth known as “May”) and again on July 14, 15 and 25 (henceforth known as “July”).

2.5 Soil moisture content and leaf area index (LAI)

Soil moisture content was measured at a depth of 20 cm using a Professional Soil Moisture Meter – Lutron PMS-714 (Digital meter Darwen, Lancashire, UK). The average of two measurements around 50 cm away from the tree stem of each tree pit was taken. The LAI of the selected trees was also measured in May and July using an AccuPAR model LP-80 PAR/LAI Ceptometer (Decagon Devices, WA). This device is a linear photosynthetically active radiation (PAR) ceptometer consisting of an integrated
probe that contains 80 PAR photodiodes and a microcontroller, which requires at least one reading above and below the canopy of a tree to estimate the LAI. It has been widely used for LAI measurement (Gu et al. 2011; Menzies et al. 2007). In this study measurements were taken between 12.00 and 16.00 h in sunny days (PAR values were between 800- 1700 µmol m$^{-2}$ s$^{-1}$).

Residential buildings were approximately 6-8 m high (2 storey) and at least 4 m away from street trees. Therefore, at the time of measurements the canopies were not shaded. For each individual tree, ceptometer measurements were taken in a circular fashion from a central position at 45 degree intervals, giving a total of eight readings. These eight measurements were then averaged. It is recommended that the sensor be properly levelled, ideally on a tripod, and the external sensor connected to the AccuPAR for above-canopy data collection. However, such an arrangement was not be feasible for quick LAI data collections in the urban settings of Manchester as radiation levels vary rapidly. Consequently, and as suggested for such environments (AccuPAR model LP-80 Operator’s Manual, Version 8), above-canopy PAR data was collected in a wide clearing outside the canopy shading.

**2.6 Leaf physiology**

Physiological and meteorological measurements were made to investigate the water status and cooling potential of the trees.

Water potential in a leaf is a measure of tree water stress. Leaf water potential was measured in both May and July between 12:00 and 16:00 h on 3 sunlit leaves removed from the mid crown of each tree, using a pressure chamber technique (Digital Plant
Stomatal conductance is a measure of the regulatory control exerted by leaf stomata to avoid water stress. Measurements of stomatal conductance were carried out in both May and July between 12:00 and 16:00 h on 3 sunlit leaves from the mid crown of each tree using the leaf porometer (model SC-1, Decagon Devices, Washington, USA). At the same time, meteorological measurements that would enable us to calculate evapotranspiration were also made. Air temperature and relative humidity were simultaneously measured in the tree shade to reduce the radiation effect, 1.5 m above the ground using a Temperature and Humidity Datalogger - CEM DT-172 (accuracy ±1%) (Digital meter, Darwen, Lancashire, UK). Measurements were logged every 5 seconds and averaged over two minutes period for each record of air temperature and relative humidity. Leaf temperatures were also recorded using the porometer at the time of measuring the stomatal conductance. Atmospheric pressure data for each measurement day were recorded from published data of the Meteorological station, Manchester Airport, UK. To check whether there was any significant difference in wind speed among the streets, wind speed at 1.5 m above ground was also measured (averaged over 5 minutes) using a hand held digital anemometer (Omega digital anemometer, model HHF92A).

The transpiration rates (E, mmol m$^{-2}$ s$^{-1}$) of leaves were finally calculated from the stomatal conductance and meteorological data using Fick’s law (Lambers et al. 1998):

$$E = g_v \times (e_{\text{leaf}} - e_a)/P_a$$  (2)
where $g_{v_{total}}$ is the total conductance to water vapour (mmol m$^{-2}$ s$^{-1}$), $e_{leaf}$ is the vapour pressure inside the leaf, which was assumed to be the saturation vapour pressure at leaf temperature, and $e_a$ is the vapour pressure of the atmosphere, calculated by multiplying the saturation vapour pressure at air temperature by the relative humidity of the air. $P_a$ is atmospheric pressure.

From equation 2, the transpiration rate was converted to g m$^{-2}$ s$^{-1}$ and multiplied by the latent heat of vapourization, which is 2.45 kJ g$^{-1}$, to calculate the energy loss per unit leaf area (W m$^{-2}$). Energy loss per tree was then calculated according to equation 3:

\[
\text{Energy loss per tree} = \text{energy loss per unit leaf area} \times \text{LAI} \times A
\]

where LAI is the leaf area index of the tree and $A$ is the crown area of the tree calculated from its crown diameter.

### 2.7 Leaf chlorophyll fluorescence (Fv/Fm)

Chlorophyll fluorescence has been used to provide a rapid and non-destructive diagnostic method for detecting and quantifying damage to the leaf photosynthetic apparatus in a variety of tree species in response to environmental stress (Resco et al. 2008; Percival 2004). Our measurements were carried out over three periods: May 18–27, July 05–12 and August 03–11, 2011. Three leaves from the lower mid canopy of each of selected 51 trees were collected and shielded from ambient light to reach a dark adapted state (30 min adaptation to the dark). Fv/Fm was measured as the ratio of maximal to variable fluorescence (Maxwell and Johnson 2000). Here, Fm is the maximum fluorescence and Fv was calculated by subtracting the minimum fluorescence (Fo) from Fm. Fv/Fm was measured by applying a saturating flash of white light provided by a quartz halogen lamp using PAM- 2000 chlorophyll fluorometer (Heinz Walz, Effeltrich, Germany).
2.8 Leaf chlorophyll analysis

The chlorophylls, Chlorophyll $a$ and Chlorophyll $b$ are the most important pigments for the conversion of light energy to stored chemical energy. Therefore, the content of these pigments can directly determine photosynthetic potential and primary production (Curran et al. 1990; Filella et al. 1995). Pigment content is closely related to plant stress and senescence (Gitelson et al. 2003). Chlorophylls were extracted from the same mature leaves collected for chlorophyll fluorescence by grinding leaf discs (2.31 cm$^2$) in a mortar. Leaf discs from 2 leaves of each tree were extracted from the midpoint of the leaf next to the main leaf vein. Chlorophyll concentration was estimated at 663.6 and 645.6 nm wavelengths and corrected for light scattering at 750 nm in a spectrophotometer (USB-2000, Ocean Optics, Dunedin, USA) after extraction with 80% v/v aqueous acetone (Porra et al. 1989). Chlorophyll content values were recorded in three terms on the same days as the Chlorophyll fluorescence measurements.

2.9 Foliar nutrient analysis

As in our previous study (Rahman et al. 2011) nutrient availability was assessed by investigating foliar levels of essential elements. Leaf samples were collected from the middle of the terminal shoot growth on August 15, 2011. Leaves were air dried, ground with a mortar and pestle and sieved with a 500 - micron sieve. Total N was determined by dry combustion method using LECO TruSpec™ CN autoanalyzer (LECO Corporation). Determination of other essential elements viz. P, K, Ca, Mg, Al, B, Co, Cu, Fe, Mn, Mo, Ni, Se, Zn and Na was carried out following standard procedure using an atomic absorption spectrometer (AAS).
2.10 Statistical analysis: Data were subjected to ANOVA and Tukey post hoc tests using SPSS V 16 software. Differences between groups were considered significant at p < 0.05.

3. Results

3.1 Tree growth and carbon sequestration

The results of the growth measurements (Fig.2) showed that there were significant differences between species in all four measurements.

A one way ANOVA showed significant differences between different tree species in height increment \[ F (4, 90) = 4.609; p < 0.01 \]; in DBH increment \[ F (4, 90) = 3.430; p < 0.05 \]; in crown diameter increment \[ F (4, 90) = 2.532; p < 0.05 \]; and in CO₂ storage \[ F (4, 90) = 4.609; p < 0.05 \]. Post hoc analyses showed that *Malus* ‘Rudolph’ had significantly lower height and DBH growth than *P. calleryana* and *Prunus* ‘Umineko’ but a higher crown diameter increment than *Prunus* ‘Umineko’. Consequently *P. calleryana* and *Prunus* ‘Umineko’ had stored significantly more CO₂ than *Malus* ‘Rudolph’.
Fig. 2 Differences in growth and stored CO$_2$ in five different tree species grown on different streets of Manchester, UK. Annual growth increments (2005–11) in (a) height, (b) DBH and (c) crown diameter and (d) Total CO$_2$ stored in April, 2011. Graphs show means ± standard error (n = 27 for *C. laevigata*, 15 for *S. arnoldiana*, 13 for *Prunus ‘Umineko’*, 26 for *P. calleryana*, and 14 for *Malus ‘Rudolph’*).

There were also significant differences between species in their LAI (Fig.3). A two way ANOVA showed significant differences between the species [$F (4, 92) = 7.48; p < 0.001$], but not between the months and there was no significant interaction between species and months surveyed. A post hoc analysis of species showed that the *C. laevigata*
and *P. calleryana* had significantly higher LAI than *S. arnoldiana* and *Prunus* ‘Umineko’.

![Figure 3](image)

**Fig. 3** Mean LAI in May and July, 2011 of five different tree species grown on different streets of Manchester, UK. Graph shows means ± standard error (*n* = 12 for *C. laevigata*, 10 for *S. arnoldiana*, 10 for *Prunus* ‘Umineko’, 10 for *P. calleryana*, and 9 for *Malus* ‘Rudolph’)

### 3.2 Soil moisture content and shear strength

There were also differences between species in soil moisture content (Fig. 4). A two way ANOVA showed significant differences in soil moisture content in the tree pits of different tree species \( F(4, 92) = 3.540; p \leq 0.05 \); however, there were no significant difference between months and no significant interaction between species and months. A post hoc analysis of species showed that the *C. laevigata*, *P. calleryana*, *S. arnoldiana* had significantly less moisture content in their tree growing pits than *Malus* ‘Rudolph’.
Fig. 4 Soil moisture content in May and July, 2011 in the top 20 cm around the tree pits of five different tree species. Graph shows means ± standard error (n = 12 for C. laevigata, 10 for S. arnoldiana, 10 for Prunus ‘Umineko’, 10 for P. calleryana, and 9 for Malus ‘Rudolph’)

There was no significant difference in soil shear strength in and around the tree pits among all the streets surveyed. Average soil shear strength was 70 ± 1.69 kP. Overall, the soil in the planting pits was similar in all the streets being mostly sandy loam in texture with around 20% clay content and very compacted. In no road has the soil strength significantly different. All the streets were very flat with little or no elevation. All the street trees received almost equal solar exposure. However, 5 Malus ‘Rudolph’ trees in Thorncliffe Grove and 3 C. laevigata in Granville Avenue were partially shaded most of the day since the gaps between the trees and the buildings in those two streets were small. There was no record of irrigation or fertilization from the city council; however, the residents living near to the street trees watered them during the first two years of tree plantings.
### 3.3 Leaf physiology

There was a significant interaction between five tree species and time in midday leaf water potentials. In May leaf water potentials of *Prunus* ‘Umineko’ and *P. calleryana* were less negative than the other tree species but not in July (Fig. 5a). A two way ANOVA showed therefore that there were significant interactions between the five tree species and time in the leaf water potential \([F (4, 92) = 5.051; p < 0.01]\), but no significant effects of the two factors themselves.

**Fig. 5** Leaf physiological parameters of five different tree species grown on different streets in May and July, 2011: (a) midday leaf water potential; (b) stomatal conductance. Graphs show means ± standard error \((n = 12\) for *C. laevigata*, 10 for *S. arnoldiana*, 10 for *Prunus* ‘Umineko’, 10 for *P. calleryana*, and 9 for *Malus* ‘Rudolph’)

There were also significant differences in stomatal conductance (Fig. 5b). A two way ANOVA showed significant differences between species \([F (4, 297) = 30.461; p < 0.001]\), between time \([F (1, 297) = 32.529; p < 0.001]\), and significant interaction between species and time \([F (3, 297) = 8.854; p < 0.001]\). Post hoc tests showed that the
stomatal conductance of *P. calleryana* was higher compared to all the other species, being 40% and over 100% higher than the other trees in May and July respectively.

### 3.4 Relationship between stomatal conductance and DBH increment

Scatter plots of average stomatal conductance of all the trees against average DBH increment showed a positive association (Fig. 6) which correlation analysis showed was significant ($r = 0.217$, $p < 0.05$). Trees that had grown faster had higher stomatal conductivity.

![Stomatal conductance vs DBH increment](image-url)

**Fig. 6** Relationship between DBH increment and stomatal conductance of five different tree species grown on different streets in May and July, 2011

### 3.5 Evapotranspirational cooling

There were large differences in evapotranspirational cooling between species and also between the months when measurements were taken (Fig.7). A two way ANOVA showed significant differences in energy loss per unit leaf area between different species [$F (4, 296) = 37.769; p < 0.001$], between months [$F (1, 296) = 22.333; p < 0.001$] and a significant interaction between species and time [$F (4, 296) = 6.880; p < 0.001$]. Post hoc
analyses showed that the energy loss per unit leaf area from *P. calleryana* was significantly higher than all other tree species and energy loss per unit leaf area from *C. laevigata* was significantly higher than *S. arnoldiana, Prunus* ‘Umineko’ and *Malus* ‘Rudolph’.

Another two way ANOVA showed that energy loss per tree was also significantly different for different tree species \[F (4, 296) = 26.062; p < 0.001\]; however, there was no significant difference between months and no interaction between species and months. Post hoc test showed that energy loss per tree was significantly higher for both *P. calleryana* and *C. laevigata* than the rest of the species. On none of the dates was there a significant difference in the wind speed at 1.5 m height between the streets, showing that the higher transpiration rates of these species were not caused by differences in wind speed.

**Fig. 7** Evapotranspirational cooling calculated for five different tree species grown on different streets in May and July, 2011 (a) energy loss per unit leaf area; (b) energy loss per tree. Graphs show means ± standard error (n = 12 for *C. laevigata*, 10 for *S. arnoldiana*, 10 for *Prunus* ‘Umineko’, 10 for *P. calleryana*, and 9 for *Malus* ‘Rudolph’)
3.6 Chlorophyll fluorescence (Fv/Fm)

Leaf chlorophyll fluorescence was highest in *P. calleryana* and lowest in *C. laevigata* (Table 2) and as the growth period continued different species responded differently. For instance *C. laevigata* showed lower fluorescence throughout the summer; fluorescence of *P. calleryana* and *Prunus ‘Umineko’* peaked in July and then started to decline; fluorescence of *S. arnoldiana* declined in July and showed some recovery in August and fluorescence of *Malus ‘Rudolph’* increased until August. A two way ANOVA showed significant differences in chlorophyll fluorescence of different tree species [F (4,135) = 8.435; p < 0.001] and significant interaction between species and time of measurements [F (8,135) = 2.532; p < 0.05]; however no significant difference between the time of measurements was found. A post hoc analysis showed fluorescence was highest in *P. calleryana* and *Malus ‘Rudolph’* followed by *S. arnoldiana* and *Prunus ‘Umineko’* and least in *C. laevigata*.

**Table 2** Chlorophyll fluorescence of five different tree species grown on different streets in May, July and August, 2011

<table>
<thead>
<tr>
<th>Species</th>
<th>May</th>
<th>July</th>
<th>August</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>C. laevigata</em></td>
<td>.76 (+ .00593)</td>
<td>.75 (+ .01340)</td>
<td>.76 (+ .01051)</td>
</tr>
<tr>
<td><em>S. arnoldiana</em></td>
<td>.80 (+ .00628)</td>
<td>.77 (+ .03664)</td>
<td>.80 (+ .00767)</td>
</tr>
<tr>
<td><em>Prunus ‘Umineko’</em></td>
<td>.78 (+ .00563)</td>
<td>.81 (+ .00387)</td>
<td>.73 (+ .03433)</td>
</tr>
<tr>
<td><em>P. calleryana</em></td>
<td>.81 (+ .00357)</td>
<td>.82 (+ .00550)</td>
<td>.81 (+ .00598)</td>
</tr>
<tr>
<td><em>Malus ‘Rudolph’</em></td>
<td>.79 (+ .00462)</td>
<td>.81 (+ .00655)</td>
<td>.82 (+ .00627)</td>
</tr>
</tbody>
</table>

* Figures in parenthesis are the standard errors of means
** Means with the same letter were not significantly different as determined by two ways ANOVA (*P* < 0.05).

3.7 Leaf chlorophyll content

Chlorophyll content of leaves showed significant differences between both species and with time (Fig.8) in both total amount and ratio of chlorophyll types. A two way
ANOVA showed significant differences in total chlorophyll content of the different tree species \( [F (4,135) = 7.723; \ p < 0.001] \) and significant difference between months \( [F (2,135) = 14.656; \ p < 0.001] \); however, no significant interaction between species and time was found. A post hoc analysis of species showed that \( P. \ calleryana \) had significantly higher chlorophyll content followed by \( C. \ laevigata \) and \( S. \ arnoldiana \) in their leaves compared to \( Malus \) ‘Rudolph’ and \( Prunus \) ‘Umineko’ leaves. A post hoc test of months showed that trees produced the highest amount of chlorophyll in July and the lowest in May. In addition to this a two way ANOVA showed significant differences in chlorophyll a: b in different tree species \( [F (4,135) = 6.502; \ p < 0.001] \) and significant difference between months \( [F (2,135) = 5.359; \ p < 0.01] \); however, no significant interaction between species and time was found. A further post hoc test of different species showed that the ratio was lowest in \( P. \ calleryana \) compared to other tree species. Moreover, a post hoc test of months showed that ratio was the lowest in August compared to May and July.

**Fig. 8** Differences in leaf chlorophyll content of five different tree species grown on different streets of Manchester in May, July and August, 2011. (a) Total chlorophyll (a+b) and (b) Chlorophyll a: b. Graphs show means ± standard error (n = 12 for C.
laevigata, 10 for S. arnoldiana, 10 for Prunus ‘Umineko’, 10 for P. calleryana, and 9 for Malus ‘Rudolph’.

### 3.8 Foliar nutrient analysis

There were significant differences in the foliar nutrient status of several elements between different tree species. Total N content of Prunus ‘Umineko’ was significantly higher than all other tree species [F (4, 19) = 214.965; p < 0.001] (Table 3). Total P content of S. arnoldiana and Prunus ‘Umineko’ were significantly higher than other tree species [F (4, 20) = 4.282; p < 0.05]. Al and Mn were significantly higher in S. arnoldiana [F (4, 20) = 6.654; p < 0.01 and F (4, 20) = 5.004; p < 0.01], B and Na were significantly higher in Prunus ‘Umineko’ [F (4, 20) = 8.894; p < 0.001 and F (4, 20) = 7.088; p < 0.01], Fe was significantly higher in C. laevigata [F (4, 20) = 4.045; p < 0.05] and Zn was significantly higher in both P. calleryana and C. laevigata [F (4, 20) = 18.101; p < 0.001].

**Table 3** Foliar nutrient status of five different tree species grown on different streets.

Leaves were collected on August 15, 2010, 12 weeks after the full bloom

<table>
<thead>
<tr>
<th>Species</th>
<th>Nutrients</th>
<th>Mean (%)</th>
<th>Mean (µg/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>P</td>
<td>K</td>
</tr>
<tr>
<td>C. laevigata</td>
<td>2.3</td>
<td>0.2</td>
<td>1.03</td>
</tr>
<tr>
<td></td>
<td>2b</td>
<td>1ab</td>
<td></td>
</tr>
<tr>
<td>S. arnoldiana</td>
<td>1.8</td>
<td>0.3</td>
<td>1.38</td>
</tr>
<tr>
<td></td>
<td>3c</td>
<td>0a</td>
<td></td>
</tr>
<tr>
<td>Prunus ‘Umineko’</td>
<td>2.8</td>
<td>0.3</td>
<td>1.03</td>
</tr>
<tr>
<td></td>
<td>2a</td>
<td>0a</td>
<td></td>
</tr>
<tr>
<td>P. calleryana</td>
<td>1.8</td>
<td>0.2</td>
<td>1.53</td>
</tr>
<tr>
<td></td>
<td>1c</td>
<td>2ab</td>
<td></td>
</tr>
<tr>
<td>Malus ‘Rudolph’</td>
<td>1.3</td>
<td>0.1</td>
<td>1.11</td>
</tr>
<tr>
<td></td>
<td>2d</td>
<td>5b</td>
<td></td>
</tr>
</tbody>
</table>

*Means with the same letter were not significantly different as determined by one way ANOVA (P < 0.05).
4. Discussion

This study has shown that there were significant differences in the rate of growth, morphology, cooling effectiveness and stress tolerance of the five different tree species, even though they had been grown in the same conditions. *Prunus* ‘Umineko’ and *P. calleryana* were the fastest growing species and *Malus* ‘Rudolph’ was the slowest growing species. In general faster growing species had a higher leaf area index and higher stomatal conductivity and so provided more cooling, though this could be at the expense of increased water stress. However, all species varied in their relationships between the different factors.

The slowest-growing tree, *Malus* ‘Rudolph’ provided low cooling, which could be related to its low LAI, low chlorophyll content, low level of foliar nutrients and low stomatal conductance. It had a large canopy spread but low leaf density and had low levels of chlorophyll a and b. However, its low water use meant that the soil around it was wetter than the other species and fluorescence showed no sign of seasonal drought stress. *Malus* ‘Rudolph’ also showed a high Chlorophyll a: b despite having low chlorophyll content. This might indicate it had low photosynthetic capabilities but had higher adaptability to stressful conditions.

Of the faster growing species *Prunus* ‘Umineko’ had surprisingly low cooling, possibly due to its low LAI and narrow canopy and because it showed signs of drought stress late on in the year. *S. arnoldiana* also had relatively low cooling because of its low LAI and stomatal conductance. The trees that provided the most cooling were *C. laevigata* and *P. calleryana*. *C. laevigata* had a wide canopy and high LAI, though it did not show great height growth, and had relatively low stomatal conductance; despite this, its large leaf
area meant that per tree it provided a large amount of cooling. The fast-growing *P. calleryana*, in contrast, provided high cooling largely because of its high stomatal conductance. Despite the high water loss, it also showed excellent drought tolerance, even showing growth and increased performance later in the year, when cooling would be more at a premium. This might be related to the fact that *P. calleryana* has a comparatively longer growth season (by 3 to 4 weeks) than all other species surveyed, so the trees continued to produce new leaves when most of the other species had stopped growing. This is similar to the findings of Peters et al. (2010) who discovered that the transpiration rate per unit canopy area of evergreen trees with higher LAI and longer growing season was almost twice as much as deciduous trees. All the species we compared were deciduous, but *P. calleryana* hold their leaves until November compared to late September or early October, 2011 for all the other species. Similar results were also reported by Bassuk et al. (2003) and Swoczyna et al. (2010). They showed that *P. calleryana* was one of the most stress tolerant species in roadside conditions among the different tree species of the USA and Poland respectively. Peters et al. (2010) found that ring porous species exercise more stomatal regulation across the growing season to protect the xylem against cavitation, so diffuse porous genera showed higher rates of water loss during June and July. All the species surveyed here were diffuse porous species, which rules out xylem anatomy as an explanation of variations in water use. The lower soil moisture content, and increased LAI and water stress at the later stage of the year is also related to *P. calleryana’s* longer growing season. Variability in water use by different tree species at different times of the year was also reported by several authors such as Kumagai et al. (2005), Oren et al. (1998) and Pataki and Oren (2003).
When Pataki and Oren (2003) compared six common deciduous species in North America, they found that drought strongly affected the canopy stomatal conductance of fast growing species such as *Liriodendron tulipifera*. For other species, the effect of drought appeared to be unusually early leaf senescence, with abscission beginning in mid to late September. This is in line with our findings for *P. calleryana* which showed stomatal regulation in the early stage of the growing season and increased stomatal conductivity with extended growth period at the later stage. However, our study found contrasting results for the fast growing species *Prunus* ‘Umineko’, which showed sign of early leaf senescence and less effect of soil moisture on stomatal conductivity. In addition we also found contrasting results for the relatively slow growing *C. laevigata* and *Malus* ‘Rudolph’ which showed increased stomatal conductivity with increased soil moisture content. The longer growth period and better adaptability of urban stress of *P. calleryana* could explain its higher chlorophyll content (both a and b) in the later stage of the year. The higher chlorophyll content of *P. calleryana* and *C. laevigata* also suggested that no damage occurred in the chlorophyll biosynthetic pathways (De Nicola et al. 2011) and can be justified as an adaptive response of these species to urban stresses. The low concentration of chlorophyll b in *Prunus* ‘Umineko’ and *S. arnoldiana* in the later stage of the year could be an indication of chlorophyll destruction by excess irradiance under the open field condition (Griffin et al. 2004). Also chlorophyll fluorescence of *P. calleryana* and *Malus* ‘Rudolph’ were within the specified range of healthy, nonstressed deciduous and evergreen trees (0.78-0.85) throughout the summer time indicating no sign of stress among those species (Demmig and Bjorkman 1987; Maki and Colombo 2001; Percival 2004). On the other hand, the constant lower chlorophyll fluorescence of *C. laevigata* might indicate its strategy of lower photosynthetic efficiency per unit leaf area.
intended to maintain denser and wider canopy, while the low late season value for *Prunus* ‘Umineko’ suggests that it is vulnerable to stress in urban areas.

What about the absolute values of cooling we found? In this study, the cooling per tree by *P. calleryana* was 1.6 and 2.2 kW tree\(^{-1}\) in May and July respectively. The values are comparable, if somewhat higher than our previous study (Rahman et al. 2011) where we got 1 and 1.4 kW tree\(^{-1}\) of cooling by *P. calleryana* grown in similar conditions in July and August respectively. The cooling capacities of all these small trees was impressive, being similar to that provided by an equivalent area of grass, but the energy loss per tree was calculated based on the transpiration rate of sunlit leaves. Although, considering the size of the canopy of those trees it is arguable that most of the leaves would have sunlight at some point of the day, it is likely that energy loss per tree would have been overestimated, because many of the leaves would have been shaded at the time of measurement. Further research, examining the water loss of street trees using weighing techniques (Montague et al. 2004) or sap flow gauges (Pataki et al. 2011) would help to determine more accurately the cooling potential of the trees.

Nevertheless, currently, at least it appears that, of the five species we studied in Manchester, *P. calleryana* and *C. laevigata* seem to provide most cooling benefits and to be most tolerant to street life, while *Malus* ‘Rudolph’, though having low cooling ability, is at least stress tolerant. *Prunus* ‘Umineko’ and *S. arnoldiana* have moderate cooling ability but seem to be more susceptible to urban stress. It must be stressed, however, that at 10-11 years of age, these are all still young trees, and the pattern might change as the trees mature, getting closer to their natural lifespan of 30-50 years.
Of course, evaporative cooling is not the only benefit of street trees. They also provide shading during the summer which can help improve human comfort. The choice of suitable species for the urban environment should also involve consideration of this contribution. In a companion paper (Armson et al. in press) we have shown that trees with higher LAI values such as *C. laevigata* and *P. calleryana* not only transpire faster, but also provide denser shade. Presumably the benefits of the higher LAI in both cases is due to the trees’ increased leaf area and hence interception of sunlight. Such high LAI trees therefore more effectively reduce heat storage in pavements and improve human comfort to a greater extent. Street trees also have an important role in reducing surface runoff by intercepting rainfall and transpiring water, and more needs to be found out about the relative ability of different species to do this. It seems that the optimal street tree should grow quickly and have a dense canopy to intercept as much sunlight and rainwater as possible. Fast growing tree species might also act to mitigate climate change as they can sequester carbon faster (Nowak, 2002) and also reduce building energy use by shading the buildings (Heisler 1986, Nowak 2000) sooner than moderate to slow-growth tree species. Finally, because of ongoing climate change and the likely increases in temperature and changes in the pattern of precipitation, major shifts in the growing seasons of trees is expected for many urban areas of the world. Keeping these in mind, more studies will be needed on the responses of urban trees to changed climatic conditions if we are successfully to use them as green infrastructure to manage the urban ecosystem.

**Acknowledgments**

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Chapter 3

Effect of Rooting Conditions on the Growth and Cooling Ability of *Pyrus calleryana*

This chapter is a reprint of a paper published in the journal of *Urban Forestry & Urban Greening*

Effect of Rooting Conditions on the Growth and Cooling Ability of

*Pyrus calleryana*

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Abstract

Urban forests appear to be an excellent way of mitigating the urban heat island and adapting cities to climate change, as trees provide cooling by evapotranspiration. However, the effects of urban growing conditions on tree growth and cooling performance have not been widely investigated. The current study addresses this shortcoming by studying the growth and leaf physiology of the commonly planted urban tree Pyrus calleryana ‘Chanticleer’. The study was carried out between February and November, 2010 on streets in Manchester, UK, where P. calleryana trees had been growing for five to six years under three contrasting growth conditions: in pavement; in grass verges; and in Amsterdam soil. Trees in Amsterdam soil had grown almost twice as fast as those in pavements, the difference being related to their lower degree of soil compaction, and hence lower shear strength. Trees grown in Amsterdam soil also had better performance in leaf physiological parameters such as stomatal conductance, leaf water potential, and foliar nutrient status. Phenological observations were also consistent with the observed differences in growth. The lower soil moisture content at 20 cm depth in Amsterdam soil also suggested there was a higher infiltration rate and more moisture available to plant roots. The enhanced growth and physiological performance of trees grown in Amsterdam soil meant they provided peak evapotranspirational cooling of up to 7kW, 5 times higher than those grown in pavements.

Key words: evapotranspirational cooling; growing conditions; shear strength; urban heat island
1. Introduction

The combined effect of the urban heat island and ongoing climate change has pushed researchers into investigating and quantifying the potential benefit of urban forests as a mitigation and adaptation tool (McPherson et al., 1997; Gill et al., 2007; Jim and Chen 2009; Shashua-Bar et al., in press). Trees cool down the local urban canopy and boundary layer through evapotranspiration and by reducing the heat storage of surface structures by shading them. Nowak (2000) reported energy cost reductions of buildings of at least 25%, and as much as 50% by planting trees in courtyards. Experiments have shown that evaporation is the dominant means by which trees dissipate the daytime radiative surplus (Oke, 1978), leading to a reduction in temperature and energy cost. However, in order to determine how much cooling urban forests provide, it is crucial to understand what controls tree growth, and the consequences of planting trees in different conditions.

According to a recent survey (Britt and Johnston, 2008), the number of street trees in England is increasing, particularly in residential and industrial areas. However, the harsh ecological conditions of the urban environment and the tree planting techniques used there place trees under increased stress. This compromises their potential growth (Roberts et al., 2006) and may reduce their effectiveness in cooling. In a large city such as Manchester, UK, thousands of vehicles and pedestrians use the streets every day which affects tree growth in many ways. Among the limiting factors are soil compaction (Randrup, 1996; Smiley et al., 2006; Bartens et al., 2009), soil moisture availability in the rooting zone (Rhoades and Stipes, 1999), nutrient deficiency, and contamination by pollutants (Jim, 1998). All these factors lead to poor growth in urban street trees in
comparison to trees in park or natural settings (Kjelgren and Clark, 1993; Close et al., 1996 I; Close et al., 1996 II; Iakovoglou et al., 2001; Leuzinger et al., 2010).

In UK cities such as Manchester, trees are usually planted using three main establishment techniques. In the conventional method, trees are planted in 1.5 m² cut-out pits in pavement and topsoil is placed in the top 50-60 cm; no measures are taken to reduce subsequent soil compaction. Another technique is to plant trees in grass verges in between the pavement and road. A more recent technique is to plant trees in structural soils, which consist of various mixtures of gravel, sand and soil. Sand-based soil, or Amsterdam tree soil (Couenberg, 1994), has a 70 – 80% sand fraction consisting of medium coarse sand with uniform particle sizes, with added organic matter and clay (Buhler et al., 2007).

The effect of these planting regimes on tree growth and cooling has not been widely investigated. Kjelgren and Clark (1992) investigated the effect of urban park, plaza, and canyon spaces on the physiology and growth of even-aged sweet gum (*Liquidambar styraciflua* L.) street trees. Close et al. 1996 (I & II) also compared the growth and phenology of sugar maple (*Acer saccharum*) trees growing in a forest and in tree lawns on urban streets. They found that trees growing in parks or forests had 50% higher growth increment and had double the stomatal conductance of trees grown in the streets. Grabosky et al. (2001) showed that street trees grown in structural and non compacted soils showed almost twice the shoot and root extension three years after planting compared to those grown in the standard pavement profiles. The objective of this study was to investigate the impact of urban planting conditions on the growth and cooling
effectiveness of a commonly planted street tree, *P. calleryana*, growing in the UK after a longer period of time (5-6 years).

### 2. Methods

#### 2.1 Site selection and *Pyrus calleryana* trees

The study was carried out over a period of 10 months between February and November, 2010, a period characterised by a cold winter up to the end of March, a dry spring and early summer up to the end of June, and a wet summer and early autumn up to the end of September. Monthly weather data from the Met office (http://www.metoffice.gov.uk/climate/uk/datasets/) for the Northwest of England and North Wales are shown in Table 1.

Table-1: Mean monthly temperature and rainfall data for the Northwest of England and North Wales between February and November, 2010.

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<thead>
<tr>
<th></th>
<th>Feb</th>
<th>March</th>
<th>April</th>
<th>May</th>
<th>June</th>
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<th>Aug</th>
<th>Sept</th>
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<td><strong>Mean rainfall (mm)</strong></td>
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</tbody>
</table>

We investigated 49 individual *P. calleryana* trees which met certain criteria. The criteria required the trees to be growing on an urban street; to be of uniform age; to have been growing under the same conditions for the same time span; and for the initial size and planting conditions of the trees to have been recorded. These criteria were met on five streets, all of which were located near the Victoria Park and Rusholme area of South Manchester. Within these streets the sites were categorised into three different growing
conditions: trees growing in 1.5 m² cut-out pits in pavements, in grass verges, and in 1.5 m² cut-out pits in pavements which had been filled with Amsterdam soil. Among the streets, Conyngham Road (53°27.2´N, 2°12.8´W) had trees in a mixture of grass verges and paved areas. Denison Road trees (53°27.3´N, 2°13.2´W) were all growing in pavements. Trees in Kent Road West (53°27.2´N, 2°13´W) and Upper Park Road (53°27.2´N, 2°13.1´W) were all growing in grass verges and trees in Thornton Road (53°27´N, 2°14.1´W) were growing surrounded by pavements but in Amsterdam soil. Trees had been planted in 2004 and 2005 at the age of 4/5 years. In total 15 trees were growing in paved street, 21 in grass verges and 13 in Amsterdam soil. Trees on paved streets and Amsterdam soil were planted in 1.2 × 1.2 m pits and those on grass verges were growing in long tree lawns along rows of different lengths but at least 0.5 m away from the edge of the nearest asphalt surface. All the street trees were in residential areas and were planted on the partition line between two houses. Planted trees were at least 7-10 m apart from each other. They were planted either on the grass verges or pavements, next to the kerb. Minimum distance to buildings was 2 m. All the studied trees were free of any visual decay symptoms, damage or dieback.

2.2 Tree growth and phenology

The tree height, DBH (Diameter at Breast Height) and canopy spread at the time of planting were all known. To compare the growth increment of trees, the total height of each tree, DBH, and canopy spreads were all measured using a measuring tape in February and March, 2010. Lateral shoot growth was also investigated by measuring five randomly selected branches from the lower canopy. The shortest distances between the lateral growth scars for the previous three years (2007-09) were measured using a 30 cm ruler. The Leaf area index (LAI) was measured on May 24, 2010 for each tree using an
AccuPAR model LP-80 PAR/LAI Ceptometer (Decagon Devices, WA). Bud burst; autumn colouration and leaf fall were recorded according to Close et al. (1996) at the initiation of bud burst, initiation of colour change, peak colour and 100% leaf fall.

2.3 Soil shear strength and moisture content

To obtain the mechanical properties of the soil, the shear strength was measured using a shear vane attached to a torque meter (model RS 575-633) in February, 2010. The vane was pressed into the soil to a depth of 50 mm and slowly rotated measuring the shear torque required. This was done at five different positions in each exposed tree pit. This gave a measurement of soil shear strength, which is related to compaction (Zhang et al., 2001). Soil moisture content was measured at two depths on two representative days of the beginning of summer and the end of summer. Soil moisture content around the tree bases at a depth of 20 cm was measured using a Professional Soil Moisture Meter - Lutron PMS-714 (Digital meter, Darwen, Lancashire, UK) on May 20, 2010 and September 21, 2010 between 12:00 and 16:00 h. The average of two measurements around each tree base was taken. Soil moisture content at a depth of 80 cm was measured using a soil augur from 17 randomly selected tree bases (5 from Amsterdam soil, 6 from paved streets and 6 from grass verges) on September, 2010.

2.4 Foliar nutrient analysis

Nutrient availability was assessed by investigating foliar levels of essential elements. Leaf samples were collected from the middle of the terminal shoot growth on August 12, 2010 according to Motsara and Roy (2008). Leaves were oven dried at 70 °C, ground with a mortar and pestle and sieved with a 500 - micron sieve. Total N was determined by dry combustion method using LECO TruSpec™ CN autoanalyzer (LECO
Determination of other essential elements viz. P, K, Ca, Mg, Al, B, Co, Cu, Fe, Mn, Mo, Ni, Se, Zn and Na was carried out following standard procedure using an atomic absorption spectrometer (AAS).

2.5 Soil nutrient analysis

Nutrient availability of soils was assessed by analyzing soil pH, organic carbon, total N, exchangeable P, K, Ca, Mg, Mn and Na. Soil samples were collected from the top 15 cm of the soil near the tree bases on March 03, 2011 and air dried at room temperature. Stones, large roots and other coarse fragments were removed using a 200 - micron sieve. Soil pH was determined using a pH meter (Mettler Toledo FE20). Organic carbon contents were determined using the calorimetric method according to Motsara and Roy (2008). Total N was determined by the dry combustion method using LECO TruSpec™ CN autoanalyzer (LECO Corporation). Available P was assessed using Bray’s method, and for available Ca, Mg, K, Na and Mn, soil samples were extracted using ammonium acetate (pH 7) (Motsara and Roy, 2008). Then soil extractants were analyzed using an atomic absorption spectrometer (AAS).

2.6 Leaf Physiology

Physiological and meteorological measurements were made on the trees on warm, cloudless days – May 25, 2010, July 28, 2010 and August 27, 2010 - to investigate the water status and cooling potential of the trees.

Water potential in a leaf is a measure of tree water stress. Leaf water potential was measured on those 3 dates between 12:00 and 16:00 h on 3 sunlit leaves removed from
the mid crown of each tree, using a pressure chamber technique (Digital Plant Water Potential Apparatus EL540-300 and EL540-305, ELE International, Hertfordshire, UK).

Stomatal conductance is a measure of the regulatory control exerted by leaf stomata to avoid water stress. Measurements of stomatal conductance were carried out on the same dates between 12:00 and 16:00 h on 3 sunlit leaves from the mid crown of each tree using the leaf porometer (model SC-1, Decagon Devices, Washington, USA). In July and August, meteorological measurements that would enable us to calculate evapotranspiration were also made. Air temperature and relative humidity were simultaneously measured in the shade, 1.5 m above the ground using a Temperature and Humidity Datalogger - CEM DT-172 (Digital meter, Darwen, Lancashire, UK). Leaf temperatures were also recorded using the porometer at the time of measuring the stomatal conductance. Atmospheric pressure data for each measurement week were recorded from published data of the Meteorological station, Manchester Airport, UK. To check whether there was any significant difference in wind speed among the streets, wind speed at 1.5 m above ground was also measured using a hand held digital anemometer (Omega digital anemometer, model HHF92A).

The transpiration rates (E, mmol m$^{-2}$ s$^{-1}$) of leaves were then calculated for the two dates in July and August from the stomatal conductance and meteorological data using Fick’s law (Lambers et al., 1998):

$$E = g_v \times \frac{(e_{leaf} - e_a)}{P_a} \quad (1)$$

where $g_v$ is the total conductance to water vapour (mmol m$^{-2}$ s$^{-1}$), $e_{leaf}$ is the vapour pressure inside the leaf, which was assumed to be the saturation vapour pressure at leaf temperature, and $e_a$ is the vapour pressure of the atmosphere, calculated by multiplying
the saturation vapour pressure at air temperature by the relative humidity of the air. $P_a$ is atmospheric pressure.

From equation 1, the transpiration rate was converted to $g \, m^{-2} \, s^{-1}$ and multiplied by the latent heat of vapourization which is 2.45 kJ g$^{-1}$ to calculate the energy loss per unit leaf area $(W \, m^{-2})$. Energy loss per tree was then calculated according to equation 2:

$$\text{Energy loss per tree} = \text{energy loss per unit leaf area} \times \text{LAI} \times A \quad (2)$$

where LAI is the leaf area index of the tree and A is the crown area of the tree calculated from its crown diameter.

2.7 **Statistical analysis**: Data were subjected to ANOVA and Tukey post hoc tests using SPSS V 16 software. Differences between groups were considered significant at $p < 0.05$.

3. **Results**

3.1 **Tree growth and phenology**

Trees in Amsterdam soil had grown almost twice as fast as those grown on the pavements and 50% faster than those grown in grass verges (Fig. 1), and had more layers of leaves in their canopy. A one way ANOVA showed a significant difference between trees grown in different planting regimes in height increment [$F (2, 46) = 14.873; p < .001$]; in dbh increment [$F (2, 46) = 75.052; p < .001$]; in crown diameter increment [$F (2, 46) = 21.517; p < .001$] and in LAI [$F (2, 45) = 47.577; p < .001$]. Post hoc analyses showed significant differences between all three groups in all four characteristics.
Figure 1: Differences in growth and morphology of *P. calleryana* grown on three different planting regimes. Annual growth increments (2004 – 10) in a) height b) DBH and c) crown diameter and d) LAI of the crown in May 2010. Graphs show means ± standard error (n = 15 for paved streets, 21 for grass verges and 13 for Amsterdam soil).

Trees in Amsterdam soil also had higher lateral extension growth over the last three years (Fig. 2), though shoot growth had generally declined over the three years. A two way ANOVA showed significant difference between planting regimes \( F (2, 138) = 22.523; p < .001 \), and between the growing years \( F (2, 138) = 9.055; p < .001 \); however, no significant interaction between years and planting regimes was found. A post hoc analysis of planting regimes showed that the shoot extension of trees grown on Amsterdam soil and grass verges was significantly higher than that of the paved streets.
It also showed that the growth rate was significantly lower in 2009-10 and 2008-09 compared to 2007-08.

Figure-2: Annual lateral shoot extension in the previous three years (2007 - 09) of *P. calleryana* grown in different planting regimes. Graphs show means ± standard error (n = 15 for paved streets, 21 for grass verges and 13 for Amsterdam soil).

Trees grown in Amsterdam soil and grass verges broke bud around a week earlier, between 26 to 28\textsuperscript{th} March, 2010, compared to 6-7\textsuperscript{th} April, 2010 in the case of trees grown in pavements (Table 2). Autumn colour also began nearly two weeks later in Amsterdam soil and grass verges – October 10 versus September 27. Peak colour occurred between October 14 and 16 for paved street trees and between October 26 and 30 for grass verges and Amsterdam soil trees.
Table-2: Phenological observations of trees growing in the three different planting regimes. Phenological observations were carried out between mid of March, 2010 and mid of December, 2010.

<table>
<thead>
<tr>
<th>Growing conditions</th>
<th>Bud break</th>
<th>Autumn colour and leaf fall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pavements</td>
<td>Not started</td>
<td>1st week of Apr.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grass verges</td>
<td>Started</td>
<td>&gt;60%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amsterdam soils</td>
<td>Started</td>
<td>&gt;70%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.2 Soil shear strength and relationship with the growth parameters

There were significant differences between the soil shear strength in the three different planting regimes \[ F (2, 46) = 20.734; p < .001 \]. A post hoc test showed that soil shear strength was significantly higher in paved streets and grass verges, more than double that of Amsterdam soil (Fig. 3).
Figure-3: Shear strength of soil around *P. calleryana* trees grown in different planting regimes. Graphs show means ± standard error (n = 15 for paved streets, 21 for grass verges and 13 for Amsterdam soil).

Scatter plots of DBH increment and LAI against soil shear strength, showed a negative association (Fig. 4). A regression analysis showed a significant effect of soil shear strength both on DBH increment (R = -0.574, *p* < .001) and on LAI (R = -0.624, *p* < .001). Trees grown on less compacted soil showed a higher growth and greater LAI.

Figure-4: Effect of soil shear strength on the growth and morphology of *P. calleryana* (a) diameter growth and (b) LAI increase.
3.3 Soil moisture content

Soil moisture content analyses showed lower moisture content in Amsterdam soil (Fig. 5) compared to the paved streets and grass verges soil. A one way ANOVA showed significant difference in soil moisture content between the planting regimes \(F (2, 80) = 28.18; p <0.001\) in the top 20 cm at the beginning of the growing season. At the end of the growing season there were also significant difference between the planting regimes \(F (2, 14) = 3.679; p \leq0.05\) in the top 20 cm. However; no significant difference was found at 80 cm.

![Soil moisture content graph](image)

Figure-5: Soil moisture content in the top 20 cm and at 80 cm depth around the bases of *P. calleryana* trees grown in different planting regimes. Graphs show means ± standard error (n = 15 for paved streets, 21 for grass verges and 13 for Amsterdam soil for 20 cm depth and n = 6, 6 and 5 respectively for 80 cm depth).

3.4 Foliar nutrient status

There were differences in the nutrient status of several elements between trees grown in the different planting regimes. Foliar N content of trees grown on Amsterdam soil and grass verges was significantly higher (Table 3) than the trees grown in the pavements \(F\)
$(2, 15) = 5.553; p<0.05$. Total P content of trees grown in the grass verges was significantly higher (Table 3) than those grown in pavements and Amsterdam soil $[F (2, 15) = 6.227; p<0.05]$. B, Mn and Na were significantly higher (Table 3) in trees grown in Amsterdam soil compared to those grown in pavements and grass verges $[F (2, 15) = 4.075; p<0.05; F (2, 15) = 6.613; p<0.01; F (2, 15) = 8.325; p<0.01]$. 

Table-3: Foliar nutrient status of tree leaves growing in the three different planting regimes. Leaves were collected on August 12, 2010, 12 weeks after the full bloom.

<table>
<thead>
<tr>
<th>Planting regimes</th>
<th>Nutrients</th>
<th>Mean (%)</th>
<th>Mean (µg/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>P</td>
<td>K</td>
</tr>
<tr>
<td>Pavements</td>
<td>1.8</td>
<td>0.1</td>
<td>0.99</td>
</tr>
<tr>
<td>Grass verges</td>
<td>2.3*</td>
<td>0.1</td>
<td>1.07</td>
</tr>
<tr>
<td>Amsterdam soil</td>
<td>2.3*</td>
<td>0.1</td>
<td>1.12</td>
</tr>
</tbody>
</table>

*Significant difference at 0.05 level  
**Significant difference at 0.01 level

3.5 Soil nutrient status

There were significant differences in soil nutrient availability in three different planting regimes. Organic carbon and total nitrogen content of soils in the grass verges were significantly higher (Table 4) than those in the pavements and Amsterdam soil $[F (2, 16) = 28.285; p< 0.01; F (2, 16) = 11.652; p< 0.01]$. Available Ca and Mg content was significantly lower in Amsterdam soil (Table 4) $[F (2, 17) = 22.244; p< 0.01; [F (2, 17) = 29.583; p< 0.01]$. Available K was significantly higher in grass verges compared to those in pavements and Amsterdam soil $[F (2, 17) = 15.439; p< 0.01]$. 

102
Table - 4: Nutrient status of the three growth media.

<table>
<thead>
<tr>
<th></th>
<th>pH</th>
<th>Organic C (%)</th>
<th>Total N (%)</th>
<th>P (µg/g)</th>
<th>Na (µg/g)</th>
<th>Mn (µg/g)</th>
<th>Ca (µg/g)</th>
<th>Mg (µg/g)</th>
<th>K (µg/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pavements</td>
<td>7.73</td>
<td>2.62</td>
<td>0.18</td>
<td>0.00</td>
<td>14.94</td>
<td>0.06</td>
<td>147.83**</td>
<td>2.40**</td>
<td>5.02</td>
</tr>
<tr>
<td>Grass verges</td>
<td>7.77</td>
<td>3.83**</td>
<td>0.25**</td>
<td>0.07</td>
<td>14.79</td>
<td>0.04</td>
<td>102.62**</td>
<td>4.00**</td>
<td>8.70**</td>
</tr>
<tr>
<td>Amsterdam soil</td>
<td>7.46</td>
<td>1.91</td>
<td>0.15</td>
<td>0.00</td>
<td>15.23</td>
<td>0.04</td>
<td>36.78</td>
<td>1.37</td>
<td>2.28</td>
</tr>
</tbody>
</table>

**Significant difference at 0.01 level

3.6 Leaf Physiology

Midday leaf water potentials of trees grown in Amsterdam soil were less negative compared to the trees grown in pavements and grass verges (Fig. 6a). One way ANOVA and post hoc tests showed significant difference between the leaf water potential of trees in May \([F (2, 144) = 27.602; p<0.001]\) and in August \([F (2, 144) = 61.100; p<0.001]\), with the leaf water potential of trees grown in Amsterdam soil being less negative than that of other streets.

![Figure-6: Leaf physiological parameters of P. calleryana trees grown in different planting regimes at three different times of the year (May, July and August, 2010): (a) midday leaf water potential; (b) stomatal conductance. Graphs show means ± standard error (n = 15 for paved streets, 21 for grass verges and 13 for Amsterdam soil).](image)

Stomatal conductance of trees growing in all three conditions was lower in the dry May, than in the wetter months of July and August. However, on all three dates, trees in
Amsterdam soil had stomatal conductance almost twice that of those grown in the pavements and 50% higher than those grown in grass verges (Fig. 6b). One way ANOVA’s showed significant difference in May \( F (2, 144) = 27.341; p<0.001 \); July \( F (2, 144) = 47.241; p<0.001 \) and in August \( F (2, 144) = 17.902; p<0.001 \). Post hoc tests showed that the stomatal conductance of trees grown on Amsterdam soil was higher than those grown in grass verges and pavements at all the three times measured and the stomatal conductance of trees grown in grass verges was higher than those grown in pavements in May and August.

3.7 Evapotranspirational Cooling

The combination of their larger canopy size, higher leaf area index, and higher stomatal conductivity, meant that the trees grown in Amsterdam soil had on average five times the rate of estimated transpiration water loss and cooling than trees grown in pavement, and almost twice that of trees grown in grass verges (Fig. 7). One way ANOVA tests showed significant differences in energy loss from trees grown in different planting regimes both in July and August \( F (2, 46) = 25.730; p < 0.001 \) and \( F (2, 45) = 57.401; p < 0.001 \). Post hoc analyses showed that the energy loss from trees grown on Amsterdam soil was significantly higher than trees grown in pavements and grass verges both in July and August.
Figure-7: Evapotranspirational cooling calculated for *P. calleryana* trees growing in three different planting regimes (n = 15 for paved streets, 21 for grass verges and 13 for Amsterdam soil).

Water losses were slightly higher in August than July for all trees because of the lower relative humidity on the streets on the days of measurements in August than July. However, on both the dates there were no significant variations in the wind speed at 1.5 m height among the streets. This shows that the higher transpiration rates of trees grown in the Amsterdam soil were not caused by differences in wind speed.

**4. Discussion**

The results showed large differences in both the growth rates and water relations of trees grown in the three different conditions. Trees in Amsterdam soil grew twice as fast as trees in pavements and 1.5 times as fast as trees in grass verges. They were also under less water stress in summer than those in pavements and grass verges. This was probably because of the different soil shear strengths, which indicates different levels of compaction. Zhang et al. (2001) have shown using the Mohr-Coulombs equation that
bulk density and soil pore water pressure are the significant determinants of soil shear strength; the higher the soil bulk density, the higher the soil shear strength. The shear strength of Amsterdam soil was less than half of that found in pavements and grass verges, and both the diameter growth increment and leaf area index of trees were inversely related to soil shear strength. These results are similar to those found in North America by several other authors (Froehlich et al., 1986; Close et al., 1996 I; Grabosky et al. 2001; Iakovoglou et al., 2001; Smiley et al., 2006). They also found that urban trees had a reduced investment in foliage production in response to urban stresses and this resulted in a substantial decline in crown spread, terminal shoot extension and LAI (Ripullone et al., 2009; Tognetti et al., 2009). Our trees grown in the pavements and grass verges probably had difficulty forcing their roots through the strong, compacted soils. Urban soil compaction usually occurs in the shallow lens of soil that would be the tree’s preferred rooting zone. For this reason, compaction of top soil contributes to insufficient rooting volumes through increasing the soil strength, usually to levels which hinder root growth (Grabosky and Bassuk, 1995; Rhoades and Stipes, 1999).

The difficulty in root penetration in pavements and grass verges probably affected the water and nutrient uptake of the trees. Results of soil moisture content suggested that Amsterdam soil had significantly lower moisture content at 20 cm, though not at 80 cm. This most likely reflects a higher infiltration rate down through the soil, and faster removal of the water by the roots in Amsterdam soil. The significantly higher nutrient status of the leaves in the trees grown on Amsterdam soil also suggests that their roots had better water and nutrient uptake. Several other studies have also described the effect of pavements and compaction on plant available moisture (Close et al., 1996 I; Close et al., 1996 II; Gomez et al., 2002; Grabosky et al., 2009) and nutrient uptake (Smiley et
al., 1985; Close et al., 1996) during the summer. Finally, the better access of trees in Amsterdam soil to water is also evident from the less negative leaf water potential of their leaves, at all times except in the wet July.

The high degree of grass roots and grasses in the topsoil of grass verges planting regime might increase the organic carbon with concomitant total N values. Exchangeable P was low in all three growing conditions as P is naturally available in very small quantities in soil solutions. Only 0.1% or less of the total phosphorus in soils is available to plants (van Straaten, 2007). Exchangeable Ca, Mg and K were significantly higher in the topsoil of grass verges and paved streets, so, there is a possibility of excessive nutrient leaching from Amsterdam soil. However, foliar nutrient status did not indicate any significant deficiency of macronutrients in the case of the trees grown in Amsterdam soil. This might be due to the more favourable rooting conditions for the trees grown in Amsterdam soil. This is further linked with the higher concentration of Na and Mn in the leaves of trees grown in Amsterdam soil, whereas no significant differences in Na and Mn concentrations were found in the soil. It also implies higher availability of nutrients for the trees grown in Amsterdam soil.

All these factors resulted in very different leaf performance in the three planting regimes. Stomatal control seemed to be the most important step to respond to drought in the dry month of May, as closing stomata would reduce the rate of water loss and so minimize water stress. All the trees showed conservative water use in May but with higher rainfall in July and August stomatal conductance increased significantly in all the trees. The stomatal conductance of trees grown on Amsterdam soil was much higher compared to the other trees, however, showing that they would have greater water loss per unit leaf.
area and consequently a higher rate of photosynthesis. Their longer-lasting leaves and earlier budding probably also helped the trees grown in Amsterdam soil to achieve their higher growth rate. These results are also in accordance with those of other authors who related physiological performance to soil compaction (Tognetti et al., 2009; Zaharah and Razi 2009).

The combination of the faster growth, more highly layered canopy, and better performance per unit leaf area of the trees grown in Amsterdam soil, meant that they evapotranspired and provided cooling at five times the rate of the trees grown in pavements. Whereas one tree grown in Amsterdam soil can provide about 7 kW of cooling in August, and 5.7 kW in July, in grass verges the figure is 3 and 2 kW in August and July respectively, and in pavements it is only 1.4 and 1 kW. Considering that the cooling capacities of room air conditioners range from 1 to 10 kilowatts, the performance of these small trees is impressive, though the energy loss per tree was calculated based on the transpiration rate of sunlit leaves. Since many of the leaves would have been shaded by the outer leaves in the canopy, energy loss per tree would probably have been overestimated. Further research, examining the water loss of street trees using weighing techniques (Montague et al., 2004) or sap flow gauges (Pataki et al., 2011) would help to determine the precise rate of water loss.

Average evapotranspirational energy loss per unit leaf area from the trees grown in Amsterdam soil was 284 W m$^{-2}$ in July and 335 W m$^{-2}$ in August. If we multiply those results by the average LAI of the trees grown in Amsterdam soil we get transpirational losses per unit crown area of 943 and 1105 W m$^{-2}$. These figures for cooling are extremely high. Using the Penman-Monteith equation and the meteorological data for the
middle of a typical July day in Manchester, one would calculate a peak energy loss per unit area of 315 W m$^{-2}$ for an adequately watered reference crop ($ET_0$) (Allen et al., 1998). Our trees were therefore 3 times as effective. The reason our trees provided so much more cooling than a patch of vegetated land, might be because transport of hot air masses above flat, dry surfaces would have caused high advective transpiration, just as washing on a line dries out faster than washing laid out on the ground. Our values were also considerably higher than the average diurnal summer evapotranspirational energy loss of well irrigated urban forest, measured using an eddy correlation approach around 225 W m$^{-2}$ reported by Grimmond and Oke (1999) in Chicago, USA. This suggests that large stands of trees would be much less effective at providing cooling, per unit crown area, than single trees, because they would have much lower advective water losses.

In conclusion, trees grown in Amsterdam soil performed better in many ways than trees grown in grass verges and especially those grown in pavements. They grew faster, developed a wider crown with more leaf layers, and showed better leaf physiological performance. As a result they provided around five times the evapotranspirational cooling compared with trees planted directly into 1.5 m$^2$ cut-out pits in pavements. Kjelgren and Montague (1998) showed that P. calleryana transpire 30% more water when growing in asphalt cut-outs than surrounded by turf. Our trees, planted in the Amsterdam soils were also growing in 1.5 m$^2$ cut-out pits in pavements but, having been planted in a better growing medium, they grew better and could even withstand short dry spells. This growing method could prove useful for producing trees that provide the cooling that the cities of the future would need even more as a consequence of future climate change. There were, however, some indications that the advantages of the Amsterdam soil might have been diminishing. A reduction in terminal shoot growth was
apparent over the last three years. Since all the other trees also had reduced terminal shoot growth, however, this might have been due to differences in the weather between the years. In support of this idea, the trees in the Amsterdam soil were still showing better physiological performance in 2010. It should be worthwhile monitoring to see if the improved performance in Amsterdam soil persists over a longer period of time.

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References


Chapter 4

Effect of pit design and soil composition on performance of *Pyrus calleryana* street trees in the establishment period

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Effect of pit design and soil composition on performance of *Pyrus calleryana* street trees in the establishment period

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Abstract

Evapotranspirational cooling from urban trees is an effective way of reducing the urban heat island. However, the appropriate planting design to maximize the cooling benefit of street trees has not been widely examined. The current study investigated the growth and physiology of a commonly planted urban tree *Pyrus calleryana* in Manchester, UK. Trees were planted in April 2010 using three standard planting techniques: in a small open pit; and in small or large closed pits with non-compacted load-bearing soils and sealed with permeable paving slabs. The growth rate, leaf area index (LAI) and stomatal conductance were monitored over the next three year growing seasons, together with chlorophyll analysis and fluorescence and leaf water potential, allowing us to determine tree health, water status and evapotranspirational cooling. Trees in the open pits grew twice as fast as those in small covered pits and 1.5 times as fast as trees in large covered pits. Having significantly higher canopy density, canopy spread and stomatal conductivity, the trees in the open pits provided up-to 1 kW of cooling, compared to around 350 and 650 W by the small and large covered pits respectively. Phenological observations, chlorophyll fluorescence, total chlorophyll and foliar nutrient content confirmed that the trees in open pits were healthier. However, the leaf water potential of trees in the covered pits were less negative, showing that they were not suffering from water stress. Instead, limited aeration probably affected their root respiration and nutrient uptake, impairing their growth and physiological performance.

Key words: Evapotranspiration; planting designs; root aeration; urban heat island
1. Introduction

The role of urban trees in adapting our cities to urban heat island is well understood (Oke 1989; McPherson et al. 1997; Shashua-Bar and Hoffman 2000; Gill et al. 2007; James et al. 2009; Leuzinger et al. 2010; Peters et al. 2010; Armson et al. in press). However, the appropriate planting design to maximize the shading and cooling benefits of urban street trees and to integrate them in the urban fabric amongst other intensely competitive land uses is still a big challenge. Along with poor quality soil, street trees in urban areas face both above and below ground space competition (Grabosky and Bassuk 1995; Jim 2001). Greater soil volume with better aeration and drainage is very important for better root growth to uptake water and nutrients, so that the trees can achieve an optimum size and provide the ecosystem functions and benefits for which we plant them. Poor tree growth incurs a high level of maintenance input and drains resources that could otherwise be devoted to other aspects of urban forestry (Jim 2001). Gilbertson and Bradshaw (1990) reported that around 23% of newly planted trees in Liverpool had died just after 3 years of planting, mainly due to limited soil volumes and increased soil compaction. In order to overcome this problem some authors have suggested mixing of different coarse matrix in the soil used for street tree planting to reduce the soil compaction and increase the load bearing capacity. For example, Kristoffersen (1998) described the possibility of expanding the rooting zone of street trees by establishing a root-friendly load-bearing growing medium under sealed pavement to carry light traffic. Grabosky and Bassuk (1995 and 1996) also suggested rock-based structural soils for improving the rooting condition of urban street trees. Subsequently, several urban planners have started to incorporate stone or sand in varying proportions with soil into major landscape improvement projects where the desired outcome is large, fast-growing trees.
However, there has been no published study which has investigated the longer term impact of these load bearing soils or the impact of sealed pavements on tree growth and physiology. Grabosky et al. (2001) showed that street trees grown in structural and non compacted soils had almost twice the shoot and root extension 3 years after planting compared to those grown in the standard pavement profiles. Studies have also shown that pavements can have significant impacts on the soil’s physical characteristics, such as soil moisture and aeration (Morgenroth and Buchan 2009). If soil pore volume and soil pore continuity are reduced by compaction or sealing, roots cannot be supplied with oxygen (Herbauts et al. 1996; Horn et al. 2007). There are some studies which showed the effect of compacted soils on the growth and rooting abundance of different tree species (Randrup 1996; Smiley et al. 2006; Bartens et al. 2009; Rahman et al. 2011). However, little information is available on how the different types of paving sealant affect soil gas diffusivity or how urban trees react to soil aeration deficiencies. Weltecke and Gaertig (2012) have shown that relative gas diffusivity at tree planting sites with asphalt, flagstone or cobblestone sealant was 10 times lower than those sites without sealing. Moreover, there was no significant difference between completely sealed (asphalt) surfaces and “water permeable” surfaces with flagstone or cobblestone with gaps in between. Even if there is sufficient moisture in compacted soil underneath the pavement, it might act as a barrier to oxygen diffusion and lead to relatively anaerobic conditions in the deeper soil profile (Morgenroth and Buchan 2009). This condition may also affect the soil fauna and microbial activity, leading to nutrient deficiency. Consequently, tree roots at roadsides could be trapped literally between the concrete surface above and poor soil below (Jim 2001).
In this study we compared three standard street planting techniques used in Manchester, UK. The first technique was the conventional method, in which trees are planted in small cut-out pits with top soil, and the other two with increased rooting volume and compaction reduction mechanisms and sealed with permeable sealing. 15 *Pyrus calleryana* ‘Chanticleer’ trees were planted in these three types of pit. The objective of this study was to test the effectiveness of these pit designs and soil composition in respect of the growth, stress tolerance and cooling potentiality of a commonly planted street tree *P. calleryana*. To do this, we measured aspects of their growth, their stress levels, and their transpiration on hot summers’ days over three growing seasons.

2. Methods

2.1 Study site

The study was carried out in Greater Manchester, UK, which is a large conurbation (population 2.5 m) located in the North West of England (Armson et al. 2012). It has a temperate maritime climate with a mean annual temperature of 9.8 °C and annual precipitation of 806.6 mm (http://www.metoffice.gov.uk/climate/uk/averages/19712000/sites/manchester_airport.html). Among the studied years, 2012 was significantly wetter (1089 mm of rainfall) than 2011 (817 mm) and 2010 (796 mm). Rainfall measurements were collected from the Whitworth Observatory around 400 m north of the experimental street.

In conjunction with the Red Rose Forest we selected Dilworth Street (53°27´47˝N, 2°14´3˝W) as our field site, since it represents a true urban setting with residential buildings in one side and commercial buildings and a university parking lot on the other
side. It is paved in black asphalt, bordered by concrete sidewalks (3-4 m wide) running from east (closed end – access to one of the University of Manchester parking lot) to west (Cecil Street) and it is 7 m wide. It was also easily accessible for the subsequent measurements and comparatively secure. 15 *Pyrus calleryana* ‘Chanticleer’ root ball (40 × 45 cm) trees with circumference of 14-16 cm at 1 m from ground, and 4-4.5 m in height were planted in April, 2010 in 3 types of pit installations. In the nursery (Barcham Trees PLC, Cambridgeshire, UK) trees were lifted as bare rooted from the field and re-grown in 65 L container for 12 months and only bottom branches were pruned. At the time of planting all the trees had comparable vigour and vitality. In Type 1 (open) pit trees were planted in 1.5 m² cut-out pits in the pavement and filled with stone free top soil – a sandy loam in structure with 15-18% clay, 20-22% silt and 60-65% sand content but no additional measures were taken to reduce compaction. In Type 2 (small covered) additional 50% course sand was added to top soil in the pit to reduce the compaction and sealed with permeable paving on top. Finally, to increase the rooting volume and reduce the compaction interlocking root-cell system filled with topsoil was used in the bigger pit size (Type 3 – large covered pit) (Table 1).
Table 1: Design of three types of pit used in the experiment

<table>
<thead>
<tr>
<th></th>
<th>Type 1</th>
<th>Type 2</th>
<th>Type 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pit dimension (m)</td>
<td>1.2 × 1.2 × 1</td>
<td>1.2 × 1.2 × 1</td>
<td>1.2 × 2.8 × 1</td>
</tr>
<tr>
<td>Soil composition</td>
<td>Top soil</td>
<td>Urban soil *</td>
<td>Special interlocking rootcell **system filled with topsoil</td>
</tr>
<tr>
<td>Irrigation set up</td>
<td>none</td>
<td>An irrigation pipe of of 895 mm × 3 m length, outside of the root barrier at 200-300 mm depth was installed</td>
<td>Same as Type 2</td>
</tr>
<tr>
<td>Root barrier</td>
<td>Only reroot 300 linear root barriers were wrapped around top of root ball</td>
<td>With linear root barrier a terram 3000 permeable geotextile layer was laid to stop upwards root growth</td>
<td>Same as Type 2</td>
</tr>
<tr>
<td>Paving material</td>
<td>Finished off with 100 mm depth of composting mulch.</td>
<td>50 mm laying course of 6 mm washed graded aggregate was laid. Finally Marshall ‘Priora’*** concrete block paving was used to seal the pit</td>
<td>Same as Type 2</td>
</tr>
</tbody>
</table>

* urban soil is a mix of 50% sand and 50% top soil; overall texture is 10-12% clay, 10-12% silt and 75-80% sand content.

**‘Root cell’ system (Green-tech Ltd, York, UK): Each cell is 250 × 250 × 90 mm in size, made of recycled high-density polyethylene (HDPE) and has a load bearing capacity of 80 tonnes per m², each cell weigh 0.38 kg and has 92% empty space inside.

*** Marshall ‘Priora’ concrete block: These are special zigzag bordered blocks with approximately 6 mm of gap between each block which allows 1.8 L S⁻¹ m⁻² water through them.
The schematic diagram of the three types of pit is shown in Fig. 1:

Figure legends
1 = Road kerb anchors
2 = Stone blinding
3 = Tree pit wall
4 = Soil
5 = Linear root barrier
6 = Irrigation pipe
7 = Concrete edging
8 = 6 mm graded stone
9 = Paving
10 = Geotextile

Figure 1: Cross-sectional design of the three pit types (adapted from tree planting design for Red Rose Forest drawn by Ombler Iwanowski Architects).

The trees were all protected by steel tree guards, 1800 mm high and 500 mm in diameter. In addition, a pair of 2.4 m high × 75 mm dia treated softwood stakes were also installed in all three types of pits, and trees were secured to the stake at approximately 1600 mm height using the twin stake and belt method. Trees were planted around 7 – 10 m apart from each other with the pit next to the kerb. To reduce any bias in conditions, trees were
planted in order in five groups, in each of which trees growing in each type of pit was
installed one after another. 9 trees were planted at the south side and the other 6 trees at
the north side of the street. At the north side, the buildings were far away from the
boundary line; therefore trees were not shaded at any time of the day. However, along the
south side, there were buildings which were approximately 7-8 m high (2 storey) and 9-
10 m away from the boundary line, so the trees were partially shaded at some point of the
day.

Continuous monitoring of street level conditions was not possible; instead, sequences of
diurnal measurements were made over 3 growing seasons. Observations were made
during the following periods:

April – November, 2010
March – November, 2011
March – November, 2012

As part of aftercare the contractor watered each tree with approximately 23 L of water at
around 1 week intervals starting from the middle of April to the middle of May in 2010
and 2011. Water was given on the open surface of type 1 pits and in the irrigation pipes
in case of type 2 and 3 pits.

2.2 Tree growth and phenology

To compare the growth increment of trees, the total height of each tree was measured
using a Suunto Clinometer, and bole height, DBH (Diameter at Breast Height), and
canopy spreads in four directions were measured biannually using a measuring tape
between April, 2010 and October, 2012. The leaf area index (LAI) of trees was
measured in May, 2010 and another eight times over the summers between 11.30 and 16.30 on warm sunny days at monthly intervals using an AccuPAR model LP-80 PAR/LAI Ceptometer (Decagon Devices, WA) along with other leaf physiological measurements. Bud burst; autumn colouration and leaf fall were recorded according to Close et al. (1996) at the initiation of bud burst, initiation of colour change, peak colour and 100% leaf fall. Autumn colouration and leaf fall were recorded in 2010, 2011 and 2012; but bud burst was recorded in 2011 and 2012 only.

2.3 Leaf physiology
Physiological and meteorological measurements were made to investigate the water status and cooling potential of trees.

Predawn leaf water potential between 2:00 and 4:00 h, mid day leaf water potential, and stomatal conductance between 12:00 and 16:00 h, were measured on the same warm sunny days on eleven dates over the 3 growing seasons. Leaf water potential was measured using a pressure chamber technique (Digital Plant Water Potential Apparatus EL540-300 and EL540-305, ELE International, Hertfordshire, UK) and stomatal conductance was measured using a leaf porometer (model SC-1, Decagon Devices, Washington, USA). For each measurement three sunlit leaves were used from the mid crown of each tree.

At the same time, meteorological measurements that would enable us to calculate evapotranspiration were also made. Air temperature and relative humidity were simultaneously measured in the tree shade to reduce the radiation effect, 1.5 m above the ground using a Temperature and Humidity Datalogger - CEM DT-172 (accuracy ±1%)
(Digital meter, Darwen, Lancashire, UK). Measurements were logged every five seconds and averaged over two minutes period for each record of air temperature and relative humidity. Leaf temperatures were also recorded using the porometer at the time of measuring the stomatal conductance. Atmospheric pressure data for each measurement day were recorded from published data of the Meteorological station, Manchester Airport, UK. To check whether there was any significant difference in wind speed among the streets, wind speed at 1.5 m above ground was also measured (averaged over five minutes) using a hand held digital anemometer (Omega digital anemometer, model HHF92A).

The transpiration rates (E, mmol m\(^{-2}\) s\(^{-1}\)) of leaves were finally calculated from the stomatal conductance and meteorological data using Fick’s law (Lambers et al. 1998):

\[
E = g_{v \text{total}} \times (e_{\text{leaf}} - e_{a})/P_{a}
\]  

where \(g_{v \text{total}}\) is the total conductance to water vapour (mmol m\(^{-2}\) s\(^{-1}\)), \(e_{\text{leaf}}\) is the vapour pressure inside the leaf, which was assumed to be the saturation vapour pressure at leaf temperature, and \(e_{a}\) is the vapour pressure of the atmosphere, calculated by multiplying the saturation vapour pressure at air temperature by the relative humidity of the air. \(P_{a}\) is atmospheric pressure.

From equation 1, the transpiration rate was converted to g m\(^{-2}\) s\(^{-1}\) and multiplied by the latent heat of vapourization, which is 2.45 kJ g\(^{-1}\), to calculate the energy loss per unit leaf area (W m\(^{-2}\)). Energy loss per tree was then calculated according to equation 2:

\[
\text{Energy loss per tree} = \text{energy loss per unit leaf area} \times \text{LAI} \times A
\]  

where LAI is the leaf area index of the tree and A is the crown area of the tree calculated from its crown diameter.
2.4 Leaf chlorophyll fluorescence (Fv/Fm)

Chlorophyll fluorescence has been used to provide a rapid and non-destructive diagnostic method for detecting and quantifying damage to the leaf photosynthetic apparatus in a variety of tree species in response to environmental stress (Percival 2004; Resco et al. 2008). We measured chlorophyll fluorescence four times each over the growing seasons of 2011 and 2012 between May and September (for technical difficulties we could not measure chlorophyll fluorescence in August, 2012). Three leaves from the lower mid canopy of each tree were collected and shielded from ambient light to reach a dark adapted state (30 min adaptation to the dark). Fv/Fm was measured as the ratio of maximal to variable fluorescence (Maxwell and Johnson 2000). Here, Fm is the maximum fluorescence and Fv was calculated by subtracting the minimum fluorescence (Fo) from Fm. Fv/Fm was measured by applying a saturating flash of white light provided by a quartz halogen lamp using PAM-2000 chlorophyll fluorometer (Heinz Walz, Effeltrich, Germany).

2.5 Leaf chlorophyll analysis

The chlorophylls, Chlorophyll a and Chlorophyll b are the most important pigments for the conversion of light energy to stored chemical energy. Therefore, the content of these pigments can directly determine photosynthetic potential and primary production (Curran et al. 1990; Filella et al. 1995). Pigment content is closely related to plant stress and senescence (Gitelson et al. 2003). Chlorophylls were extracted from the same mature leaves collected for chlorophyll fluorescence by grinding leaf discs (2.31 cm²) in a mortar. Leaf discs from two leaves of each tree were extracted from the midpoint of the leaf next to the main leaf vein. Chlorophyll concentration was estimated at 663.6 and 645.6 nm wavelengths and corrected for light scattering at 750 nm in a
spectrophotometer (USB-2000, Ocean Optics, Dunedin, USA) after extraction with 80% v/v aqueous acetone. Chlorophyll content values were recorded in eight terms according to (Porra et al. 1989) on the same days as the Chlorophyll fluorescence measurements.

### 2.6 Foliar and soil nutrient analysis

As in our previous studies (Rahman et al. 2011; Rahman et al. in press) nutrient availability was assessed by investigating foliar levels of essential elements. Leaf samples were collected from the middle of the terminal shoot growth on August 15, 2011 and August 29, 2012. Leaves were air dried, grounded with a mortar and pestle and sieved with a 500 - micron sieve. Total N was determined by dry combustion method using LECO TruSpec™ CN autoanalyzer (LECO Corporation). Determination of other essential elements viz. P, K, Ca, Mg, Al, B, Co, Cu, Fe, Mn, Mo, Ni, Se, Zn and Na was carried out following standard procedure using inductively coupled plasma atomic emission spectroscopy (ICP-AES).

Soil analysis was carried out to determine soil pH, organic carbon and total N of soils used in three types of pits. Soil samples were collected from the top 15 cm of the soil near the tree bases from three pits of each type of pit on April 26, 2013 and air dried at room temperature. Stones, large roots and other coarse fragments were removed using a 200 µm sieve. Soil pH was determined using a pH meter (Mettler Toledo FE20). Organic carbon contents were determined using the calorimetric method according to Motsara and Roy (2008). Total N was determined by the dry combustion method using LECO TruSpec™ CN autoanalyzer (LECO Corporation).
2.7 Statistical analysis: Data were subjected to ANOVA and Tukey post hoc tests using SPSS V 20 software. Differences between groups were considered significant at p <0.05.

3. Results

3.1 Tree growth and phenology

Trees in the open pits grew almost twice as fast as those grown in small covered pits and 50% faster than those grown in large covered pits (Fig. 2 a & b). A one way ANOVA showed significant differences between trees grown in different types of pits in height growth \( F(2, 27) = 3.955; p < 0.05 \); in DBH growth \( F(2, 27) = 17.691; p < 0.001 \). Moreover, trees grown in open pits showed almost three times higher crown diameter increment than those grown in small covered pits (Fig. 2 c). Another one way ANOVA showed significant differences between trees grown in three types of pits in crown diameter growth \( F(2, 12) = 4.425; p < 0.05 \) and a post hoc analysis showed that trees grown in open pits grew significantly higher in terms of height, DBH and crown diameter than those grown in small and large covered pits.
Figure 2: Annual growth rate in *Pyrus calleryana* trees grown in the three pit types in 2010-2012 (n = 5): (a) height, (b) DBH and (c) crown diameter increment.

Trees grown in open pits also had more layers of leaves (Fig. 3) compared to those grown in small and large covered pits. A two way ANOVA showed significant differences in LAI of trees grown in three different types of pits between the planting pits \( [F (2, 108) = 6.103; p < 0.01] \), between the time \( [F (8, 108) = 53.837; p < 0.001] \), but no significant interaction between the planting pits and time. Post hoc tests showed that LAI of trees grown in open pits was higher compared to the trees grown in small and large covered pits. Moreover, post hoc analysis also showed that LAI was higher in mid to late summer compared to the early summer time.
Figure 3: LAI of *Pyrus calleryana* trees grown in the three pit types in 2010-2012 (n=5)

Trees grown in large covered and open pits finished breaking their buds around 5-8 days earlier, between March 29 and April 5 compared to April 8-12 in the case of the trees grown in small covered pits (Table 2). Autumn colour also peaked nearly two weeks later in large covered and open pits, around the 3rd week of November versus the 1st week of November for small covered pits.
Table 2: Phenological observations on *Pyrus calleryana* trees grown in the three pit types. Observations were carried out between mid March and mid December, 2011 and 2012 and between mid September and mid December, 2010.

<table>
<thead>
<tr>
<th>State</th>
<th>2nd week March</th>
<th>1st week April</th>
<th>3rd week Sept.</th>
<th>3rd week Oct.</th>
<th>1st week Nov.</th>
<th>3rd week Nov</th>
<th>1st week Dec</th>
<th>3rd week Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small covered pit</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bud break</td>
<td>Started</td>
<td>&gt;60%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Autumn colour</td>
<td></td>
<td>~12%</td>
<td>~40%</td>
<td>Peak</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leaf fall</td>
<td></td>
<td></td>
<td>&gt;30%</td>
<td>&gt;80%</td>
<td>Completed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large covered pit</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bud break</td>
<td>Started</td>
<td>&gt;70%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Autumn colour</td>
<td></td>
<td>~10%</td>
<td>~20%</td>
<td>~45%</td>
<td>Peak</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leaf fall</td>
<td></td>
<td></td>
<td>&gt;20%</td>
<td>&gt;50%</td>
<td>&gt;90%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open pit</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bud break</td>
<td>Started</td>
<td>&gt;80%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Autumn colour</td>
<td></td>
<td>~10%</td>
<td>~20%</td>
<td>~30%</td>
<td>Peak</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leaf fall</td>
<td></td>
<td></td>
<td>&gt;15%</td>
<td>&gt;40%</td>
<td>&gt;80%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 3.2 Leaf physiology

There were also significant differences in mid day leaf water potential (Fig. 4a) and pre dawn leaf water potential (Fig. 4b) of trees grown in the three different types of pits and between different times when measurements were taken. A two way ANOVA showed significant differences in mid day leaf water potential between the planting pits [F (2, 330) = 4.722; p < 0.05], and between times [F (10, 330) = 63.415; p < 0.001], but no significant interaction between the planting pits and time. Post hoc tests showed that mid day leaf water potential of trees grown in small and large covered pits were less negative compared to those grown in open pits. Post hoc tests also showed that mid day leaf water potential was less negative towards the end of summer compared to the early summer time.
Another two way ANOVA showed significant differences in predawn leaf water potential between the planting pits \([F (2, 332) = 6.008; \ p < 0.01]\), between time \([F (10, 332) = 80.373; \ p < 0.001]\), and significant interaction between the planting pits and time \([F (20, 332) = 10.408; \ p < 0.001]\). Post hoc tests showed that predawn leaf water potential of trees grown in open pits and small covered pits were less negative than those grown in large covered pits. Post hoc test also showed that predawn leaf water potential was less negative during the mid summer compared to the early and late summer time.

Stomatal conductance of trees grown in the three types of planting pits was not significantly different for the first two measurement dates in 2010; however, the trees grown in open pits showed significantly higher stomatal conductivity throughout the measurement dates thereafter, except on 21.05.2012 (Fig. 5). A two way ANOVA showed significant differences between the planting pits \([F (2, 462) = 40.316; \ p < 0.001]\),
between times \( F \ (10, 462) = 53.837; \ p < 0.001 \), and a significant interaction between the planting pits and times \( F \ (20, 462) = 2.962; \ p < 0.001 \). Post hoc tests showed that the stomatal conductance of trees grown in open pits was higher compared to trees grown in small and large covered pits. Moreover, post hoc analysis also showed that stomatal conductance was higher in late summer compared to the early summer time.

![Figure 5: Stomatal conductance of leaves of *Pyrus calleryana* trees grown in the three pit types in 2010-2012 (n=5)](image)

3.3 Evapotranspirational cooling

There were large differences in evapotranspirational cooling provided by the trees grown in the three different types of planting pits and also between different times when measurements were taken (Fig. 6). A two way ANOVA showed significant differences in energy loss per tree between the planting pits \( F \ (2, 462) = 60.884; \ p < 0.001 \), between times \( F \ (10, 462) = 19.712; \ p < 0.001 \) and a significant interaction between the planting pits and time \( F \ (20, 462) = 3.859; \ p < 0.001 \). Post hoc analyses showed that the energy loss from trees grown in open pits was significantly higher than those grown in small and large covered pits and energy loss from trees grown in large covered pits was higher than those grown in small covered pits. Moreover, post hoc analysis also showed that energy
loss was higher during the mid summer time compared to the late or early summer and cooling ability of trees increased along with the age of the trees.

![Figure 6: Evapotranspirational cooling of Pyrus calleryana trees grown in the three pit types in 2010-2012 (n=5)](image)

3.4 Chlorophyll fluorescence (Fv/Fm)

There were also significant differences in the Fv Fm ratio of trees grown in the three different types of planting pits and between different times when measurements were taken (Fig. 7). A two way ANOVA showed significant differences between the planting pits \[F (2, 84) = 26.813; p < 0.001\] and significant differences between times \[F (6, 84) = 26.299; p < 0.001\]. Post hoc tests showed that Fv Fm ratio of trees grown in open and large covered pits were higher than those grown in small covered pits. Post hoc test also showed that the ratio was higher during mid to late summer compared to the early summer time.
Figure 7: Chlorophyll fluorescence in leaves of *Pyrus calleryana* trees grown in the three pit types in 2011-2012 (n=5)

### 3.5 Total Chlorophyll

Total Chlorophyll content (a and b) of tree leaves showed significant differences between both planting pits and with time (Fig. 8). A two way ANOVA showed significant differences between the planting pits \([F (2, 96) = 29.570; p < 0.001]\) and between time \([F (7, 96) = 13.687; p < 0.001]\); however, no significant interaction between the planting pits and time. Post hoc tests showed that total chlorophyll content of tree leaves grown in open pits was higher than both small and large covered pits and total chlorophyll content of tree leaves grown in large covered pits was higher than those grown in small covered pits. Moreover, post hoc test also showed that the total chlorophyll content of leaves of trees grown in three different types of pits were higher in mid to late summer compared to that of early summer time.
Figure 8: Total chlorophyll content (a+b) of leaves of *Pyrus calleryana* trees grown in the three pit types in 2011-2012 (n=5)

3.6 Foliar and soil nutrient status

There were differences in the nutrient status of several elements between trees grown in different types of planting pits (Table 3). One way ANOVA showed foliar N, P, K, Fe, Mn and Zn content of trees grown in open pits were significantly higher than those grown in small and large covered pits \[F (2, 27) = 11.386; p < 0.001; F (2, 27) = 6.058; p < 0.01; \] \[F (2, 27) = 4.963; p < 0.05; F (2, 27) = 8.739; p < 0.001; F (2, 27) = 3.386; p < 0.05 and F (2, 27) = 4.535; p < 0.05 respectively\].
Table 3: Foliar nutrient status of *Pyrus calleryana* trees grown in the three pit types. Leaves were collected on August 15, 2011 and August 29, 2012 approximately 12/14 weeks after the full bloom.

<table>
<thead>
<tr>
<th>Planting pit technique</th>
<th>Nutrients</th>
<th>2011&amp;12 Mean (%)</th>
<th>Mean (µg/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>P</td>
<td>K</td>
</tr>
<tr>
<td>Small covered</td>
<td>1.2</td>
<td>0.1</td>
<td>1.2</td>
</tr>
<tr>
<td>Large covered</td>
<td>1.6</td>
<td>0.1</td>
<td>1.3</td>
</tr>
<tr>
<td>Open</td>
<td>1.9</td>
<td>0.1</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Soil pH, organic carbon and total N content of top soil used in the open pits was also higher compared to the soil used in the small and large covered pits. Average soil pH of top soil in the open pits (7.21) was significantly higher than the small covered (6.99) and large covered (6.98) pit [F (2, 6) = 8.22; p < 0.05]. Organic carbon and total nitrogen content of topsoil used in the open pits (3.49% and 0.26%) was also significantly higher compared to the small covered pits (2.21% and 0.17%) and large covered pits (2.20% and 0.17%)[F (2, 6) = 25.709; p < 0.01; F (2, 6) = 25.709; p < 0.01 respectively].

4. Discussions

The study has shown that there were significant differences in the rate of growth, morphology and cooling effectiveness of trees grown in the three different planting pits. The tree in the open pits performed best; they grew twice as fast as in small covered pits and 1.5 times as fast as trees in large covered pits. The difference continued to increase over the growing seasons. In terms of morphology also they showed almost three times more crown spread increment compared to those grown in small covered pits and 1.5
times more than those in large covered pits. Canopy density varied among the months surveyed, but trees grown in open pits showed significantly higher density throughout the experiment and the trend was even more visible towards the end of the experiment. In general, with significantly higher stomatal conductivity, trees grown in open pits provided cooling more than double the amount by those grown in small covered pits and 1.5 times more than those grown in large covered pits.

It might be thought that these differences occurred because the paving on the covered planting pits reduced water infiltration into the pit, which would have caused them increased drought stress and reduced their nutrient uptake. However, both the mid day and predawn leaf water potential of the trees grown in the small covered pits were actually significantly less negative compared to those grown in large covered and open pits, showing that these trees were less water stressed. In contrast, the concentration of most important macronutrients such as N, P, K and micronutrients such as Fe, Mn and Zn in the leaves of trees grown in open pits was significantly higher than those grown in small and large covered pits. Trees in the open pits also broke bud 1 week earlier and had leaf fall 2 weeks later compared to those grown in small covered pits. This suggests that the poor performance of the covered trees is due not to water deficit, but to the lack of oxygen which would hinder deeper rooting and ultimately affect the foliar investment and leaf gas exchange. This is certainly in line with the results of other studies (Morgenroth and Buchan 2009; Morgenroth 2011; Weltecke and Gaertig 2012). Morgenroth and Buchan (2009) and Morgenroth (2011) investigated the effect of pervious and impervious pavements on soil moisture content and aeration and in turn on the root growth of *Platanus orientalis* seedlings over two growing seasons. They found high moisture content underneath the pavement surface irrespective of permeability but a
lack of aeration. Subsequently the shallow root abundance was higher underneath the pavements but only in the case of unpaved plots did the seedlings achieve deeper rooting. It seems plausible that due to the sealing or reduced soil pore volume, the soil moisture content was higher in the upper soil layers, just as we found that tree planting pits with higher soil strength had increased soil moisture content in the upper 20 cm of the soil profile (Rahman et al. 2011). Consequently trees grown in small and large covered pits developed a shallow root system and showed reduced growth and physiological performance despite not being under water stress.

Leaf water potential corresponded generally well with rain events during the study. Following dry springs, both midday and predawn leaf water potential of tree leaves grown in the three different types of pits were more negative. The sharp contrast in terms of planting techniques are that the trees grown in the open pits showed a significantly more negative midday leaf water potential than those in covered pits (small and large) but in terms of predawn leaf water potential, trees grown in large covered pits were more negative. This might be due to the pavement effect which reduces evaporation during the day time but at night releases absorbed heat and evaporates more water from the soil compared to the open pit. Nevertheless, Nielsen et al. (2007) argued that soil hydrology is not always the driving mechanism of tree transpiration in street planting pits. Reduced soil pore volume and continuity due to sealing in the case of both the small and large covered pits might affect the root respiration and nutrient uptake of trees (Herbauts et al. 1996; Horn et al. 2007) leading towards reduced growth and stomatal conductivity. Moreover, top soil in the open pits might have more opportunity of the retention and accumulation of nitrate delivered by atmospheric deposition although they are more vulnerable to leaching compared to the sealed pits. Lower C and N content of soils under
paving surfaces were predictable and are in line with other authors such as Raciti et al. 
(2012) who reported around 66% and 95% decrease in C and N content in the soil (0-15 
cm) under impervious surfaces in New York City.

Macronutrients such as nitrogen are also a dominant factor affecting the plant Chl a and 
are generally related to productivity (Filella et al. 1995). This might explain the higher 
chlorophyll content for trees grown in open pits. The higher chl a+b contents in leaves of 
trees grown in open pits suggest that no damage had occurred in the chlorophyll 
biosynthetic pathways (De Nicola et al. 2011). Chlorophylls not only absorb light but 
also funnel the excitation energy from Photosystem I to Photosystem II and the 
depression of Fv/Fm has consequently been used as an indicator of nutrient stress or 
imbalance (Kruskopf and Flynn 2006). Trees grown in the open pits also showed 
efficient use of light captured with their higher chlorophyll content in terms of better 
photochemical efficiency of PS II (Fv/Fm). Moreover, chlorophyll fluorescence of the 
trees grown in the open and large covered pits were within the specified range of the 
healthy, non-stressed deciduous and evergreen trees (0.78-0.85) throughout the summer 
time, indicating no sign of stress among those trees (Demmig and Bjorkman 1987; Maki 
and Colombo 2001; Percival 2004). Although there are reports that stomatal conductance 
is not directly determined by photosynthetic capacity (e.g., von Caemmerer et al. 2004), 
Matsumoto et al. (2005) showed that the stomatal conductance variability depended 
markedly on chlorophyll function and the degree of dependence was almost equal to that 
on solar radiation or vapour pressure deficit.

All these factors together contributed towards a 40% increase in stomatal conductance of 
trees grown in open pits compared to those grown in small covered pits. Combined with
a higher leaf area index and canopy spread, this meant that trees grown in open pits provided around 1 kW of cooling in June, 2012. Although, the total energy loss per tree was calculated based on the transpiration rate of sunlit leaves, there is a chance of overestimation, since many of the leaves would have been shaded at the time of measurements. Ansley et al. (1994) compared the whole tree transpiration rate based on porometer measurements with stem flow using sap flow gauges. They reported that the values were comparable; however, during the peak transpiration time (mid day), porometer measurements might overestimate the whole tree transpiration rate. But, considering the size of the canopy of those trees it is arguable that most of the leaves would have sunlight at some point of the day.

Projecting the cooling ability of those trees grown in open pits over the next three growing season using existing stomatal conductivity and LAI but extending the canopy at the previous rate of growth, gives a figure for cooling rate of around 7 kW. This is comparable to our previous study in which P. calleryana trees were grown for six years in open pits with a non-compacted sand-based soil (Rahman et al. 2011). Similarly, we can predict that the cooling ability of those P. calleryana trees grown in the small covered pits after three more growing season would be around 1.1 kW between June and August. This value is comparable, if somewhat smaller than our previous findings for P. calleryana trees grown in highly compacted pits after six years of planting (Rahman et al. 2011 and Rahman et al. in press). In this way trees grown in small covered pits are losing the advantages of growing in non-compacted soil due to sealing. The experimental design for this study was opportunistic, based on three commonly used planting techniques by the Red Rose forest in Manchester, UK. There is a chance of confounding effect of soil composition and pit design. However, the consistency of the results across
the studied years negated the advantages of better soil composition (both in terms of top soil filled in root cell systems or mixing with sand) by the pit design. In this way the study further emphasize the importance of aeration which might be equally or even more important for growth and cooling ability of trees as soil compaction.

However, it must be stressed, these trees are all still very young in their establishment age and the pattern might change as the trees mature, getting closer to their natural lifespan of 30-50 years. Once they start to break out of the confines of the pit, soil condition in the road site situation and the impervious pavement over root zones can confound other urban stresses on tree growth and physiology, since the trees on unrestricted rooting zone can extend as much as three times the dripline distance from the trunk (Gilman, 1988). However, impervious pavements are not equally deleterious to all species when grown in urban conditions and researcher such as Quigly (2004) showed that early successional species such as *P. calleryana* in our case might maintain a similar rate of growth rate after a longer period of establishment compared to the late-successional species. Future tree size in relation to available soil volume in the establishment stage is another consideration. Researchers such as Buhler et al. (2007) showed that trees planted in bigger sized pits (>12 m²) proved to be the best in terms of growth and vitality after 15 years of planting in Copenhagen, Denmark compared to trees planted in smaller sized pits with or without structural soil.

In conclusion, in this study, trees grown in open pits performed better in many ways than trees grown in large covered and especially compared to those grown in small covered pits. They grew faster, developed a wider crown with more leaf layers, better stress tolerance and showed better leaf physiological performance. As a result they provided
around double the amount of evapotranspirational cooling compared to trees planted in small covered pits and 1.5 times than those in large covered pits. However, our experimental site was in an uncrowded university-owned street, so there was not enough footfall to cause soil compaction in the open pits. The extra layer of composting mulch might also have helped the trees grown in open pits in their establishment period. If no compaction reduction measure is taken in case of open pits in busy streets they might start losing their benefit of good soil aeration and reduce their growth and physiological performance. Therefore, large covered pits and other comparable methods might have an advantage in the long term if incorporated with techniques to increase soil aeration, such as sealing the surface with criss-crossed iron structures. Our previous experiment showed better tree growth and physiological activities for *P. calleryana* trees grown in open cut-out pits planted with sand based soil (Rahman et al. 2011). Therefore it might be a good idea to incorporate structural soil with an open surface or sealed with perforated structures for better growth and cooling performance of street trees. Finally, it would be worthwhile to monitor the effect on root growth and also the effect of ongoing climate change on different establishment methods in order to successfully manage our urban ecosystems.

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Chapter 5

Effect of urbanization and climate change in the rooting zone on the growth and physiology of *Pyrus calleryana*

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Effect of urbanization and climate change in the rooting zone on the growth and physiology of *Pyrus calleryana*

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Abstract

It is well known that trees can reduce the urban heat island and adapt our cities to climate change through evapotranspiration. However, the effects of urbanization and anticipated climate change in the soil-root rhizosphere have not been widely investigated. The current study studied the growth and physiology of the urban tree Pyrus calleryana grown in a factorial experiment with or without urbanisation and simulated climate change between April, 2010 and December, 2012 in the Botanical Grounds of the University of Manchester, UK. The study indicated that urbanization and simulated climate change had small but contrasting effects on tree growth and morphology. Urbanization increased tree growth by 20-30%, but did not affect leaf area index (LAI) and showed reduced peak water loss and hence evapotranspirational cooling. Although soil moisture content in the upper 20 cm was higher in the urbanized plots, urbanization showed reduced sap flux density, reduced chlorophyll a :b and delayed recovery of chlorophyll fluorescence (Fv :Fm) throughout the experimental period. In contrast, simulated climate change had no effect on growth but increased LAI by 10%. Despite being more water stressed, trees grown in simulated climate change plots lost more water both according to porometry and sap flow measurements. Simulated climate change increased peak energy and water loss by around 13%, with trees having an average sap flux density of around 170 g cm$^{-2}$ d$^{-1}$, 40% higher than trees grown in control plots. Our study suggested that transpirational cooling benefit might be enhanced with a longer growth season and higher soil temperature in places such as Manchester, UK in future, but potentially at the expense of photosynthesis and carbon gain.

Key words: evapotranspiration; peak water loss; sap flux density; simulated climate change
1. Introduction

The creation of the urban heat island (Wilby, 2003; Graves et al., 2001) and the role of urban trees in adapting our cities to urban heat island is well understood (Oke, 1989; Shashua-Bar and Hoffman, 2000; Gill et al., 2007; Ennos, 2010; Peters et al., 2010). However, tree growth and the evapotranspirational cooling benefit of urban trees can be seriously hampered by the harsh ecological conditions where they are planted. Soil compaction (Randrup, 1996; Smiley et al., 2006; Rahman et al., 2011), soil aeration (Morgenroth and Buchan, 2009; Weltecke and Gaertig, 2012), soil moisture availability (Rhoades and Stipes, 1999) and soil temperature (Cox and Boersma, 1967; Graves et al., 1989; Cochar d et al., 2000; Mellander et al., 2004; Day et al., 2010) are the most critical factors. Evapotranspirational cooling also varies with the climate, tree species and environmental conditions (Oke, 1989; Shashua-Bar and Hoffman, 2000; Catovsky et al., 2002; Pataki and Oren, 2003; Peters et al., 2010; Rahman et al., in press). In the UK, climate change is predicted to cause a 2-4 °C increase in air and soil temperature, a 30% increase in the winter rainfall and 30% decrease in summer rainfall by the 2080s (Gill et al., 2007). All these factors might affect root growth directly or indirectly and have alter urban tree growth and cooling potentiality.

Our previous studies have shown that stress factors such as soil compaction or soil aeration due to urbanization can reduce evapotranspirational cooling of a commonly planted urban tree *Pyrus calleryana* in Manchester, UK by a factor of as much as 4-5 (Rahman et al., 2011; Rahman et al., unpublished). However, little is known how climate change and urbanization will interact in their effects on tree growth and physiology. Researchers such as Montague et al. (2004) and Hagishima et al. (2007) have investigated the water use of potted plants arranged in varying urban landscaping
compositions. However, the growth and the energy budgets of potted plants are different from those of mature trees in the field. Wang et al. (2011) attempted to correlate the transpiration rate of six urban tree species with environmental variables in Beijing, China by measuring the sap flow and reported that the transpiration of urban trees depends mainly on two interrelated environmental factors: heat and water.

Due to the lack of evapotranspirational cooling on urban surfaces, they can heat up in the sun. A study at Urbana-Champaign, Illinois showed soil temperatures were 4.1 °C higher at 10 cm depth than in forested sites nearby (Johnson et al., 1975). Climate change is another important driver of soil temperature. The predicted warmer wetter winters and hotter drier summers in the UK will further increase the soil temperature of urban areas (Gill et al., 2008). Increased soil temperature can reduce soil and plant hydraulic conductance and water uptake (Kramer and Boyer, 1995) by increasing water viscosity and membrane permeability and also by reducing new fine root production. However, dendrochronological studies have indicated increased root growth during warmer growing seasons (e.g., McKenzie et al., 2001; Bunn et al., 2005), leading to a positive relationship between temperature and growth in northern forests (D'Arrigo et al., 2008).

In explaining the dynamics of water flow in trees many factors are important (Mellander et al., 2004), such as vapour pressure deficit and water availability due to evaporation and freezing. In addition to the reduced summer rainfall, increased soil evaporation might reduce the amount of soil moisture available for the tree growth and transpiration.

In urban areas soil compaction may also limit gas exchange and impose root aeration stress (Day et al., 2010). The compacted soil and pavement might increase the water content of the soil but decrease the macroporosity and reduce root penetration (Skinner et
In addition, reducing photosynthetic acclimation can be accompanied by the reduction in chlorophyll concentration and chlorophyll fluorescence (Percival et al., 2006; Ow et al., 2011), since soil compaction and temperature is also associated with the relegation of nutrient fluxes in the soil (Mellander et al., 2004). Considering all these factors, the objective of this study was to quantify the sensitivity of the growth and cooling potential of a commonly planted urban tree species Pyrus calleryana to urbanization and climate. To do this, we grew 20 trees in a factorial experiment with two factors: urbanization and climate change. We studied the effects of the treatments on soil temperature and water availability and measured how the treatments affected the tree growth, morphology, physiology and their cooling potential.

2. Methods

2.1 Study site and experimental design

The study was carried out in Greater Manchester, UK, a large conurbation (population 2.5 m) in North West England (Armson et al., 2012). It has a temperate maritime climate with a mean annual temperature of 9.8 °C and annual precipitation of 806.6 mm (http://www.metoffice.gov.uk/climate/uk/averages/19712000/sites/manchesterairport.html). The experiment was set up inside the Botanical Grounds of the University of Manchester. To allow comparisons and correlations with different environmental factors important for the transpiration and growth of trees, sensors were installed with data loggers to continuously record meteorological data. Air temperature was monitored using a HOBO® 12 bit temperature smart sensor (accuracy < ± 0.2 °C from 0 ° to +50 °C) (Onset Computer Corporation, MA, USA) that was mounted in a solar radiation shield near to the plots at 2 m height and the cable was connected to the datalogger. Wind speed
was also monitored using a HOBO® wind speed meter (accuracy ± 4% of reading). Rainfall measurements were collected from the Whitworth Observatory around 2 miles north of the Botanical Grounds. Among the studied years, 2012 was significantly wetter (1089 mm of rainfall) than 2011 (817 mm) and 2010 (796 mm). The mean air temperature between April and September was 14.3 °C in 2011 and 13.1 °C in 2012. The total amount of precipitation between April and September was 337 mm in 2011 and 632 mm in 2012.

To investigate the impacts of urbanization and climate change on *Pyrus calleryana* trees, we used a randomized block factorial experiment in a plot 15 × 7.5 m. The total area was split into 20 (1.8 × 1.8 m) plots. 20 *P. calleryana* trees of 14-16 cm at 1m stem height were planted in April 06, 2010 and were assigned randomly to one of four treatments; control (ON), urbanised (UN), climate change (OC), and urbanised plus climate change (UC). For the control trees, the soil was levelled after weeding without causing any intentional compaction. For the 10 urbanized trees, in contrast, the plots were repeatedly compacted using a garden roller and were then paved using Richmond natural concrete flags (450 mm × 450 mm × 35 mm) leaving a 900 × 900 mm open space around the tree bases. To test uniformity, the soil shear strength was measured using a shear vane meter (model RS 575-633) at five different points of each plot. This gave us an indication of soil compaction (Zhang et al., 2001). The average soil shear strength of urbanized plots was 68 ± 0.46 kPa compared to 47 ± 0.87 kPa for non-urbanized plots at 50 mm depth. For the 10 climate change plots, the soil temperature of the upper 30 cm was raised by 2-3 °C (following the assumption of Roderfeld et al., 2008) using soil heating cables. Authors such as Mark et al. (2012) have reported around 1.5 °C soil temperature increase for every 1 °C air temperature rise. Moreover, many studies also have shown the creation
of below ground “heat islands” directly beneath the pavements (Celestian and Martin 2004; Montague and Kjelgren 2004; Mueller and Day 2005). For example, authors such as Byrne (2006) have shown soil underneath the pavements can be up to 8–20°C warmer than that of lawn or bark-covered soils. Therefore, 48.8 m long soil heating cables were laid 15-20 cm beneath the surface of soil and spaced 15 cm apart from each other through the plots to be warmed. The controller was set to increase soil temperature by up to 3 °C compared to the control plots; however, on few occasions (data not shown) soil temperature of OC and UC plots increased by up to 8 °C depending on the radiation balance. For monitoring soil temperature, 8 HOBO® 12 bit temperature smart sensors were inserted 10 cm in the soil in 8 plots (2 for each treatment) and were connected directly to a data logger.

To simulate the anticipated rainfall pattern in 2080s in Manchester (Gill et al., 2007), partial rainfall exclusion (-30%) was achieved during May to November using a system of rainfall collecting buckets and hose pipes suspended at about 0.3 m above the ground and re-routing the intercepted water far away from the plots for the period of summer and autumn using the current rainfall as baseline. For each plot three buckets equal to 30% area in size were used. The reverse was done during winter and spring (December-April) by routing the extra 30% water into the climate changed plots from outside to simulate the higher expected winter rainfall due to climate change. This simulation of changes in the rainfall pattern is also within the range of the UK climate change projections 2009 output (Murphy et al., 2009). According to the projections the biggest changes in precipitation in winter, increases up to +33% are seen in the Western side of the UK and down to about -40% in parts of Southern England by 2080 in case of Medium emission scenario (having the baseline climate as 1961-90).
In selecting the study site, urban soil condition was also considered. The soil of the site represents typical urban growth conditions at least at Manchester, UK (similar to Rahman et al., 2011). There were fragments of brick and concrete ranging from 1 to 2 cm of around 5% of the total soil volume. The soil itself was sandy loam in structure with 15-20% clay, 15-20% silt and 60-70% sand content. A chemical analysis of soil in April, 2013 showed around 3% organic matter and 0.19% total nitrogen content with a drainage capacity of 3-3.5 cm hr\(^{-1}\).

2.2 Tree growth and phenology

To compare the growth increment of trees, the total height of each tree was measured using a hand-held clinometer (Suunto USA, Carlsbad, CA), and bole height, DBH (Diameter at Breast Height at 1.37 m), and canopy spreads in four directions were measured biannually using a measuring tape between April, 2010 and November, 2012. The leaf area index (LAI) of trees was measured in August, 2010 and another seven times over the summers between 11.30 and 16.30 on warm sunny days at monthly intervals using an AccuPAR model LP-80 PAR/LAI Ceptometer (Decagon Devices, WA) along with other leaf physiological measurements (due to technical difficulties LAI was not measured in July, 2012). Bud burst; autumn colouration and leaf fall were recorded according to Close et al. (1996) at the initiation of bud burst, initiation of colour change, peak colour and 100% leaf fall. Autumn colouration and leaf fall were recorded in 2010, 2011 and 2012; but bud burst was recorded in 2011 and 2012 only.

2.3 Soil moisture content

Soil moisture content was measured at a depth of 20 cm using a Professional Soil Moisture Meter – Lutron PMS-714 (accuracy ± 5%) (Digital meter Darwen, Lancashire,
The average of the two measurements around 50 cm away from the tree stem of each tree pit was taken on eight dates over two growing seasons (2011 & 2012) along with other leaf physiological measurements.

### 2.4 Leaf physiological measurements

Physiological measurements were made to investigate the water status and cooling potential of trees.

Predawn leaf water potential between 2:00 and 4:00 h, mid day leaf water potential, and stomatal conductance between 12:00 and 16:00 h, were measured on the same warm sunny days on nine dates over the three growing seasons. Only on one occasion in 2010 and two occasions in 2012 was stomatal conductance taken either a couple of days earlier or later than the leaf water potential measurements due to the weather conditions. Leaf water potential was measured using a pressure chamber technique (Digital Plant Water Potential Apparatus EL540-300 and EL540-305, ELE International, Hertfordshire, UK) and stomatal conductance was measured using a leaf porometer (accuracy ± 10%) (model SC-1, Decagon Devices, Washington, USA). For each measurement three sunlit leaves were used from the mid crown of each tree. At the same time, meteorological measurements that would enable us to calculate evapotranspiration were also made. The transpiration rates (E, mmol m\(^{-2}\) s\(^{-1}\)) of leaves were calculated from the stomatal conductance and converted to the energy loss per unit leaf area (W m\(^{-2}\)). Finally, energy loss per tree was calculated by multiplying the energy loss per unit leaf area with LAI and the crown area of the tree (details are described in Rahman et al., 2011).
2.5 Leaf chlorophyll fluorescence (Fv/Fm)

In response to environmental stress chlorophyll fluorescence has been used as a good indicator for detecting and quantifying damage to the leaf photosynthetic apparatus in a variety of tree species (Percival et al., 2006; Resco et al., 2008). We measured chlorophyll fluorescence four times over each of the growing seasons of 2011 and 2012 between May and September. Three leaves from the lower mid canopy of each tree were collected and shielded from ambient light to reach a dark adapted state (30 min adaptation to the dark). Fv/Fm was measured as the ratio of maximal to variable fluorescence (Maxwell and Johnson, 2000). Here, Fm is the maximum fluorescence and Fv was calculated by subtracting the minimum fluorescence (Fo) from Fm. Fv/Fm was measured by applying a saturating flash of white light provided by a quartz halogen lamp using PAM-2000 chlorophyll fluorometer (Heinz Walz, Effeltrich, Germany).

2.6 Leaf chlorophyll content

The chlorophylls, especially chlorophyll a and chlorophyll b are the most important pigments for the light harvesting and channel the excitation energy to the photosynthetic reaction centres. Therefore, the content of these pigments can directly determine photosynthetic potential and closely related to plant stress and senescence (Gitelson et al., 2003). Chlorophylls were extracted from the same mature leaves collected for chlorophyll fluorescence by grinding leaf discs (2.31 cm²) in a mortar. Leaf discs from 2 leaves of each tree were extracted from the midpoint of the leaf next to the main leaf vein. Chlorophyll concentration was estimated at 663.6 and 645.6 nm wavelengths and corrected for light scattering at 750 nm in a spectrophotometer (USB-2000, Ocean Optics, Dunedin, USA) after extraction with 80% v/v aqueous acetone. Chlorophyll
content values were recorded in eight terms according to Porra et al. (1989) on the same
days as the chlorophyll fluorescence measurements.

2.7 Foliar nutrient analysis
As in our previous studies (Rahman et al., 2011; Rahman et al., in press) nutrient
availability was assessed by investigating foliar levels of essential elements. Leaf
samples were collected from the middle of the terminal shoot growth on August 15, 2011
and August 29, 2012. Leaves were air dried, grounded with a mortar and pestle and
sieved with a 500 - micron sieve. Total N was determined by dry combustion method
using LECO TruSpec™ CN autoanalyzer (LECO Corporation, Michigan, USA).
Determination of other essential elements viz. P, K, Ca, Mg, Al, B, Co, Cu, Fe, Mn, Mo,
Ni, Se, Zn and Na was carried out following standard procedure using inductively
coupled plasma atomic emission spectroscopy (ICP-AES) (Perkin-Elmer Optima 5300).

2.8 Sap flux density
Sap flux density was measured on eight randomly selected trees, two from each of the
four different treatments according to Granier (1987). Thermal dissipation probes (TDP
30, Dynamax, Houston, TX, USA) were placed in the outer 3 cm of xylem, on the north
facing side of each tree at breast height (1.37 m). The probes were radially inserted into
the sapwood approximately 15 cm apart. The probes and the surrounding portion of the
stem were wrapped with a layer of plastic bubble-wrap and then with a aluminium foil to
minimize radiant heating of the stem as well as to protect against water running down the
trunk (Wang et al., 2011). Instantaneous sap flux density (Js g cm⁻² s⁻¹), was continuously
measured using thermal dissipation probes, from April 18 to September 30, 2012. Due to
power failures, there were discontinuations in the sap flux recordings; nonetheless the trends were apparent and the disruptions statistically did not affect the data analysis.

These outputs were converted to sap flux density (Js) in the sapwood according to the empirical formula of Granier (1987) (equation 1):

\[ Js = 0.0119 \left( T_m - T \right)^{1.231} / T \]  

(1)

where \( T_m \) and \( T \) are the temperature differences of heated and unheated needles at no flow and positive xylem flow conditions, respectively. The temperatures were continuously scanned 10s interval and the average of every five minute was stored in data loggers (CR1000, Campbell Scientific Inc., UK). Sap flow was calculated by multiplying the sap flux density with sap wood area (we considered the radius of the whole tree at dbh for sap wood area calculation).

Among the sap flow measurement techniques, the Granier method has been particularly popular due to its simplicity, degree of accuracy, reliability, and low cost (Lu et al., 2004), however; authors such as Renninger and Schafer (2012) reported around 20-35% underestimation of sap flow estimation using the Granier method especially in ring-porous species. As \( P. \) calleryana, is a diffuse porous species, the chance of underestimation is low. However, it has been suggested that one should calibrate each new species to which Granier type sensors are applied (Lu et al., 2004); this was not possible in our study due to the destructive harvesting necessary for the calibration process. Nevertheless, many studies have also shown that the original calibration coefficient is relatively independent of wood anatomy or tree species (Catovsky et al., 2002; Lu et al., 2004). Finally, since our trees were quite young (dbh range between 4.6 and 5.3 cm and height range between 3.5 to 4.5 m on April, 2011) we assumed little or
negligible pith inside the wood and did not consider spatial variations (radial, circumferential and axial) in sap flux density in the stem.

2.9 **Statistical analysis:** Data were subjected to ANOVA and Tukey post hoc tests using SPSS V 20 software. Differences between groups were considered significant at p < 0.05.

3. Results

3.1 **Tree growth and phenology**

Urbanisation, but not climate change had significant effects on tree growth (Fig. 1). A three way ANOVA showed urbanisation significantly increased both dbh increment \[F (1, 32) = 5.807; p < 0.05\] and crown diameter increment \[F (1, 32) = 4.903; p < 0.05\] by 21\% and 32\% respectively. There was also a significant 2-way interaction between urbanization and climate change in case of dbh increment \[F (1, 32) = 4.596; p < 0.05\]; climate change increased the dbh of trees grown in urbanized plots but decreased it in non-urbanized plots.
Figure 1: Differences in growth of *P. calleryana* grown in four different treatments. Annual growth rates (2010-12): a) height b) dbh c) crown diameter. Graphs show means + standard error (n =5).

In contrast, LAI was significantly affected by both climate change and time but not urbanisation (Fig. 2). A three way ANOVA showed climate change increased LAI by 10% [F (1, 128) = 14.669; p < 0.001] and there were also significant difference between the times [F (7, 128) = 11.446; p < 0.001]. A post hoc test showed that the LAI was higher in mid to late summer compared to early summer.
Figure 2: Differences in LAI of *P. calleryana* grown in 4 different treatments over three growing seasons (2010-12). Graph show means ± standard error (n =5).

The trees grown in climate change plots showed 10-12 days of extended growth period compared to urbanized plots (Table 1) and peak autumn colour and completion of shedding of leaves took place nearly a week later.
Table 1: Phenological observations of trees grown in the four different treatments.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Bud break</th>
<th>Autumn colour and leaf fall</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2nd week of March</td>
<td>1st week of April</td>
</tr>
<tr>
<td>ON</td>
<td>Started</td>
<td>&gt;80%</td>
</tr>
<tr>
<td>UN</td>
<td>Started</td>
<td>&gt;70%</td>
</tr>
<tr>
<td>OC</td>
<td>Started</td>
<td>&gt;90%</td>
</tr>
<tr>
<td>UC</td>
<td>Started</td>
<td>&gt;75%</td>
</tr>
</tbody>
</table>

3.2 Soil moisture content

There were also differences between treatments in soil moisture content (Fig. 3). A three way ANOVA showed a significant effect of urbanization \([F (1, 288) = 61.519; p \leq 0.001]\), climate change \([F (1, 288) = 60.106; p \leq 0.001]\) and time \([F (7, 288) = 35.694; p \leq 0.001]\) in soil moisture content in the tree plots of different treatments. Urbanization increased the soil moisture content by 17% and climate change reduced the soil moisture content by 15%. A post hoc analysis showed that the soil moisture content of all treatments were significantly higher in 2012 than 2011.
Figure 3: Soil moisture content in 2011 and 2012 in the top 20 cm around the tree bases in four different treatments. Graph show means ± standard error (n =5).

3.3 Leaf physiology

The mid day leaf water potential (Fig. 4a) and pre dawn leaf water potential (Fig. 4b) of trees grown in the four different treatments showed a significant effect of urbanization, climate change and time. A three way ANOVA showed that urbanization made mid day leaf water potential 4% less negative \([F (1, 304) = 4.639; p \leq 0.05]\), while time also had a significant effect \([F (8, 304) = 81.709; p \leq 0.001]\). A post hoc test showed that trees were under more water stress in 2011 compared to 2012; in early summer compared to mid to late summer.
Figure 4: Differences in leaf water potential of *P. calleryana* grown in 4 different treatments measured over 3 growing seasons (2010-12): a) mid day b) pre dawn. Graphs show means ± standard error (n =5).

Another three way ANOVA showed that climate change made predawn leaf water potential 12% more negative  [F (3, 304) = 6.655; p ≤ 0.001], while time also had a significant effect [F (8, 304) = 28.658; p ≤ 0.001]. There were also significant 2-way interactions between urbanization and time [F (8, 304) = 4.086; p ≤ 0.001]; and between climate change and time [F (8, 304) = 2.639; p ≤ 0.01]; urbanization reduced the water stress over the measurement dates and climate change increased the water stress over the measurement dates. A post hoc test also showed that predawn leaf water potential was more negative in 2011 compared to 2012 and 2010; in early summer compared to the mid to late summer.
3.4 Evapotranspirational cooling

Stomatal conductance of trees grown in the four different treatments was not significantly different throughout the measurement dates (Fig. 5a); however, a three way ANOVA showed a significant effect of time $[F (8, 504) = 108.818; p \leq 0.001]$ and a 2-way interaction between climate and time $[F (8, 504) = 2.417; p \leq 0.05]$. A post hoc test showed that the stomatal conductance was higher in 2012 compared to 2011 and 2010 and towards the end of summer compared to the early summer. Nevertheless, there were significant differences in evapotranspirational cooling provided by the trees grown in the four different treatments and also between the times when measurements were taken (Fig. 5b). A three way ANOVA showed that climate change increased evapotranspirational cooling by 13% $[F (1, 504) = 10.525; p \leq 0.01]$ and time also had a significant effect $[F (8, 504) = 122.417; p \leq 0.001]$, but urbanisation did not. A post hoc test showed that the energy loss from trees was higher in 2012 compared to 2011 and 2010 and towards the end of summer compared to the early summer.

Figure 5: Leaf physiological performance and evapotranspiration cooling capabilities of *P. calleryana* trees grown in different treatments over 3 growing seasons (2010-12): (a) stomatal conductance; (b) energy loss. Graphs show means ± standard error (n =5).
3.5 Chlorophyll analysis

Chlorophyll content and chlorophyll fluorescence of leaves showed significant effects of urbanization and time (Fig. 6) in both the ratio of chlorophyll types (a and b) and chlorophyll fluorescence. A three way ANOVA showed that urbanisation reduced chl a:b by 5% \([F (1,128) = 5.795; \ p < 0.05]\) and time also had a significant effect \([F (7,128) = 21.359; \ p < 0.001]\). There was also a 2-way interaction between urbanization and climate change \([F (1,128) = 5.554; \ p < 0.05]\); climate change increased the chlorophyll ration of trees grown in urbanized plots but decreased it in non-urbanized plots. A post hoc test also showed that chlorophyll a:b was higher in 2011 compared to 2012 and the ratio was higher towards the end of summer compared to the early summer.

Figure 6: Chlorophyll analysis of \(P. \ calleryana\) trees grown in 4 different treatments measured over 2 growing seasons (2011-12): a) Chlorophyll a:b b) Chlorophyll fluorescence (Fv/Fm). Graphs show means \(\pm\) standard error (n =5).

Another three way ANOVA showed that Fv:Fm of leaves of trees was affected by all three factors. Urbanization reduced the ratio by around 0.005 \([F (1,128) = 4.373; \ p <\)
0.05], climate change increased it by 0.005 [F (1,128) = 4.666; p < 0.05] and time also had a significant effect [F (7,128) = 66.054; p < 0.001]. A post hoc test showed that Fv: Fm was higher towards mid to late summer compared to the early summer.

3.6 Foliar nutrient status

There were not large differences in the foliar nutrient status of different elements between trees grown in different treatments (Table 2). A three way ANOVA only showed a significant effect of urbanization in reducing Ca content [F (1, 32) = 5.623; p < 0.05]; Mg content [F (1, 32) = 5.844; p < 0.05] and increasing B content [F (1, 32) = 8.477; p < 0.01] of leaves of trees grown in the urbanized plots.

Table 2: Foliar nutrient status of tree leaves grown in 4 different treatments. Leaves were collected on August 15, 2011 and August 29, 2012 approximately 12/14 weeks after the full bloom.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>2011&amp; 12 Nutrients</th>
<th>Mean (%</th>
<th>Mean (µg/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>P</td>
<td>K</td>
</tr>
<tr>
<td>ON</td>
<td>2.06</td>
<td>0.34</td>
<td>1.27</td>
</tr>
<tr>
<td>UN</td>
<td>2.13</td>
<td>0.30</td>
<td>1.33</td>
</tr>
<tr>
<td>OC</td>
<td>0.13</td>
<td>0.17</td>
<td>2.87</td>
</tr>
<tr>
<td>UC</td>
<td>2.18</td>
<td>0.34</td>
<td>2.48</td>
</tr>
</tbody>
</table>

*Means with the same letter were not significantly different as determined by one way ANOVA (P < 0.05).
3.7 Sap flow analysis

There were significant differences in sap flux density (Js) both between times of the year and due to the treatments under which the trees were growing (Fig. 7). A three way ANOVA showed that urbanization reduced Js \[ F (1, 548) = 11.935; p < 0.01 \] by 12%, climate change increased it by 44% Js \[ F (1, 548) = 98.367; p < 0.001 \] and time also had a significant effect \[ F (5, 548) = 30.276; p < 0.001 \]. A post hoc analysis showed that Js was significantly higher in August, May, September and July compared to June and April, and was significantly higher in June compared to April, 2012.
Figure 7: Sap flux density (Js) of trees grown in 4 different treatments between April 18 and September 30, 2012: a) daily sums of sap flux density where each panel represents the mean of 2 trees measured for each treatment b) average sap flux density, where each panel represents the average of daily sap flux density of 2 trees over the growing season
measured for each treatment. Error bars show the standard error (n = 143). There are missing values due to equipment failure.

In terms of whole tree sap flow, the effect of climate change was larger than that of urbanization (Fig. 8). Another three way ANOVA showed climate change increased the total sap flow by 21% [F (1, 548) = 27.281; p < 0.001]. Time also had a significant effect [F (5, 548) = 31.012; p < 0.001]. Like sap flux density post hoc analysis showed that sap flow was significantly higher in the months of August, May, September and July compared to June and April, and was significantly higher in June compared to April, 2012.
Figure 8: Sap flow of trees grown in 4 different treatments between April 18 and September 30, 2012: a) daily sums of sap flow where each panel represents the mean of 2 trees measured for each treatment b) average sap flow, where each panel represents the average of daily sap flow of 2 trees over the growing season measured for each
treatment. Error bars show the standard error (n = 143). There are missing values due to equipment failure.

4. Discussion

The current study indicated that urbanisation and simulated climate change had small but contrasting effects on tree growth and morphology; urbanization increased tree growth by 20-30%, whereas simulated climate change had no effect on growth but increased the LAI by 10%. Climate change also extended the growing period by delaying autumn colour and leaf shedding. Porometry suggested that neither urbanisation nor simulated climate change affected leaf physiology, but due to low LAI and stomatal conductivity of trees grown in the urbanized plots compared to those in the climate change plots, urbanization reduced peak water and energy loss. Overall water loss, determined by sap flow measurements, supported a somewhat different pattern; though urbanization decreased mean sap flux density, it had no effect on mean sap flow because urbanised trees had thicker trunks. Simulated climate change, in contrast, increased water loss.

So what caused the effects on water loss? It was not related to the lower water availability in urbanised plots, since the soil moisture content in the upper 20 cm was significantly higher in urbanized plots. Moreover, midday leaf water potential showed a significant positive effect of urbanization, while predawn leaf water potential showed a negative effect of climate change. However, the results did show a negative effect on chlorophyll a:b, reduced recovery in chlorophyll fluorescence, reduced amount of Ca and Mg content in the leaves of trees grown under urbanized treatments. Therefore, in the current study water availability was not an issue for those trees grown in the urbanized plots; it is more likely that aeration might have influenced the soil-root environment. This
effect of urbanization is in line with the findings that the effect of compaction (Randrup, 1996; Smiley et al., 2006; Rahman et al., 2011) or impervious pavement (Morgenroth and Buchan, 2009) is particularly detrimental to tree growth. Increase in the soil available water with light to moderate compaction in UN or UC plots is also consistent with the findings of other authors (Craul, 1985; Jim, 1993). The combination of increased volumetric water content, and decreased macroporosity might have influenced gas diffusion and may cause root aeration stress (Day et al., 2010).

On the other hand, despite being more water stressed, trees grown under simulated climate change showed around 40% higher sap flux density compared to those grown under control conditions. Probably the warmer soil temperature facilitated an increased uptake of water by fine roots. Considerable evidence suggests that rises in soil temperature increase the metabolic activities of soil microbes (Chapin et al., 1995; Zak et al., 1999) and roots grow faster (McMichael and Burke, 1998). Graves et al. (1989) showed positive effect on leaf area, stem length, root-to-shoot ratio, and shoot and root dry weights of tree-of-heaven *Ailanthus altissima* when the soil temperature was increased from 18 to 24 °C but diminished growth and leaf conductance at 30 °C. In fact, optimal temperature for root growth varies widely (according to Lyr and Hoffman (1967) between 2 °C and 25 °C) but usually corresponds to the native temperature regime (McMichael and Burke, 1998; Day et al., 2010). *P. calleryana*, which is native to temperate China, might get the benefit of few degree C increases in soil temperature within the stated range.

The study showed little effect on chlorophyll or nutrient status but that fluorescence was affected by urbanization. Despite having a lower soil moisture content and a slower
growth rate, trees grown under simulated climate change still maintained a higher canopy density and mean evapotranspirational cooling. One possible explanation for this is that trees were in the optimal range of soil temperature and even their reduced supply of summer precipitation was still enough to maintain higher stomatal conductance. Moreover, with warmer soil temperature, *P. calleryana* might have invested more on foliage to transpire more compared to the other trees and thus have lower dbh but higher LAI. Another possible explanation of early bud break but reduced stem growth might be that any early spring root growth that preceded the development of photosynthetically functional new leaves would have to be fuelled by the utilization of stored non-structural carbohydrates (Pregitzer et al., 2000).

Of course in the current study we tried to simulate only the soil temperature and soil moisture availability in our climate change plots and investigated their effect on growth and transpirational cooling potentiality of a commonly planted urban tree species in Manchester, UK. However, in reality predicted climate change will also cause other biotic and abiotic changes which would modify the effects on tree growth and cooling potentiality. Different general circulation models suggested a 2-5 °C mean rise in the global air temperature with CO₂ doubling in 2100, with greater warming in higher latitude than near equator (Xu et al., 2007). Although there is still apprehension about the effect of climate change on tree growth and ecosystem services provided by them, the impact of higher air temperature and CO₂ have been well documented. In general, increased temperature increases tree growth, except for tropical trees (Way and Oren, 2010). With anticipated climate change there are likely to be increases in both day and night time temperature. Transpiration is significantly driven by the difference in vapour pressure between the inside of leaves and the humidity of the surrounding air. If day and
night temperatures increase to the same extent, then vapour pressure deficits would increase with increasing temperature (Kirschbaum, 2004), increasing the cooling ability further. However, the primary effects of increased atmospheric CO$_2$ concentrations on woody plants include reductions in stomatal conductance, hence transpiration rate, but increased growth and aboveground biomass production (Kirschbaum, 2004; Smith et al., 2013). Researchers have shown reduction in stomatal conductance by about 20-40% when CO$_2$ concentration was doubled (Morison, 1985; Allen, 1990; Bert et al., 1997). Therefore, any stomatal closure might have negated any increase in transpiration with increased air temperature.

In conclusion, our study suggests that predicted climate change in the tree rhizosphere in Manchester, UK should if anything increase their cooling potential. However, the studied years were very wet and trees were only growing in situ for three years. Therefore, water availability was not a problem. However, in drier years or places climate change might impose serious drought stress. However, increased transpirational cooling might potentially be at the expense of photosynthesis and carbon gain. Predicting ecosystem responses to climate change considering the spatial heterogeneity of urban microclimates is always a complex and challenging task. Therefore, these results should be verified and extended by carrying out further experiments with bigger sample sizes, different species and under a range of microclimatic conditions.

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Chapter 6

General Discussion
6.1 Introduction

Chapter 1 outlined the issues associated with ongoing climate change and urbanization in the creation of the urban heat island. It was recognized that urban greenspaces are the most feasible option to mitigate the urban heat island and adapt our cities to climate change. The subsequent chapters investigated the relative effectiveness of different tree species, the effect of rooting conditions and the effect of simulated climate change on the growth and cooling abilities of urban trees. This final chapter will compare the performance of the different tree species and of trees under differing growth conditions in terms of their cooling ability per unit area, so that they can be more readily used in regional and local energy exchange models.

6.2 Summary of findings

To strengthen adaptation and mitigation efforts at local levels, urban greenspaces are increasingly recognised as a vital tool in overcoming some of the negative conditions found in the heavily managed built environment. Previous studies have attempted to quantify the potential benefit of urban greenspaces to alleviate the urban heat island (Oke, 1989; McPherson et al., 1997; Shashua-Bar and Hoffman, 2000; Gill et al., 2007; James et al., 2009; Ennos, 2010; Leuzinger et al., 2010; Peters et al., 2010; Armson et al., 2013). However, evapotranspirational cooling varies with tree species, growth conditions and climate (Catovsky et al., 2002; Pataki and Oren, 2003; Peters et al., 2010).

The first study (Chapter 2) showed that the urban cooling provided by evapotranspiration in trees grown in conventional pits in pavements varied greatly depending on the species. Peak energy loss per tree was almost the same for *P. calleryana* and *C. laevigata* (around 1950 W tree\(^{-1}\)), but this was double the amount provided by *Malus* ‘Rudolph’ (965 W
tree$^{-1}$), 3 times higher than *S. arnoldiana* (628 W tree$^{-1}$), and 4 times higher than *Prunus* ‘Umineko’ (502 W tree$^{-1}$). However, when considering peak energy loss per unit leaf area, it was found that the value for *P. calleryana* (355W m$^{-2}$) was around 1.5 times higher than *C. laevigata* (240 W m$^{-2}$) and more than double that of the rest three tree species (170 W m$^{-2}$).

There did not seem to be a clear relationship between peak cooling and growth, which supports previous findings that stomatal conductivity is not always directly related to growth rate (Kirschbaum, 2004; Smith et al., 2013). However, the trees which provided the most cooling had the broadest (*C. laevigata*) or densest (*P. calleryana*) crowns, which also led them in the sister study (Armson et al., 2013) to provide the deepest shade, lowering surface temperatures by the greatest amount of 17 °C. Authors such as Peters and McFadden (2010) have also shown that LAI is more important in reducing the soil and surface temperature than even the plant functional type. They reported that across the growing season that forest areas with high leaf area index had soil temperatures that were 7° C lower and surface temperatures that were 6° C lower than sites with low leaf area index.

In order to optimize the cooling benefit of urban trees we also have to understand the factors that control tree growth and physiology. As discussed in Chapter 1 good quality soil, greater soil volume with better aeration and drainage (Grabosky and Bassuk, 1995; Jim, 2001) and low soil compaction (Randrup, 1996; Smiley et al., 2006; Bartens et al., 2009) in the rooting zone are all crucial for better root growth to uptake water and nutrients. In the second study, therefore, (Chapter 3) we investigated *P. calleryana* trees of the same age as we had surveyed in our previous study (Chapter 2), but grown in
different streets of Manchester in three contrasting rooting conditions. We showed that growth conditions can alter the cooling ability of trees even more than the species. Trees grown in 1.5 m² cut-out pits in the pavements grew and performed very differently depending on the type of soil in which they were grown. Trees planted in compaction-resistant Amsterdam soil, which had lower shear strength, had almost double the growth rate and had 5 times higher cooling ability. Trees in Amsterdam soil also showed better performance in terms of growth and water relations compared to those trees grown in grass verges. When the results are expressed in per unit leaf area, the average peak cooling ability of trees grown in Amsterdam soil was 310 W m⁻² compared with 153 W m⁻² for trees grown in grass verges and 126 W m⁻² for trees grown in normal compacted soil.

Following this demonstration of the problems of soil compaction, our next experiment (Chapter 4) showed that even having non-compacted sand based soil was not sufficient to ensure good tree growth and performance. The experiment showed that if the soil above the root system was sealed, even with pervious paving, in the trees’ establishment period, tree growth was reduced, probably because it impeded movement of oxygen to the roots. In this experiment, trees in open pits grew and cooled the environment at almost twice the rate as those grown in sealed small pits and 1.5 times faster than those grown in bigger sealed pits. The average peak cooling ability of trees in terms of per unit leaf area over the three years grown in the open pit was 205 W m⁻² compared to 140 W m⁻² for trees grown in small covered pits and 152 W m⁻² for those grown in bigger covered pits. It is possible that the small open pits with topsoil might have got compacted in time, if they had been situated in busy streets and consequently tree growth and cooling benefit might have been reduced, just as they were in the street trees studied in Chapter 3.
Therefore, possible ways of optimising growth might be to have more open “grid”
structures around street trees in city centre sites and to plant trees in grass verges in sand
based soils in less busy suburban sites. The latter solution has the added benefit of the
cooling effect of grasses which might not compete for water and nutrients with trees as
they take soil moisture and nutrients from the shallowest layer of the soil. If we could
calculate the water loss per unit area of common grasses we would also be able to
calculate their contribution to cooling, which could be used in modelling studies.

There is also a knowledge gap regarding the feedback of climate change on urban trees
themselves. In our final experiment (Chapter 5) we studied the effect of urbanization and
simulated climate change in the soil-root rhizosphere of *P. calleryana* trees. In this study
in which we used a sandy loam soil, trees grown in compacted urbanized plots showed a
20-30% increase in growth. This was unexpected, especially in light of the results of our
second experiment (Chapter 3), but trees in the urbanised plots did show reduced
physiological activities including water loss which is in accordance with the results of other studies such as those of Tognetti et al. (2009); Zaharah and Razi (2009). Authors
such as Mosena and Dillenburg (2004); Alameda and Villar (2009) also reported that
moderate soil compaction caused growth increases in seedlings of 17 woody species
(both evergreen and deciduous) inside a greenhouse. In contrast to the effect of
urbanisation, in our experiment simulated climate change had little effect. The average
peak energy loss over a period of three years in terms of watts per unit leaf area was 240;
220; 250 and 230 W m⁻² for trees grown in ON; UN; OC and UC plots. These values of
peak energy loss were slightly higher than the same aged *P. calleryana* trees grown in the
open pits (Chapter 4), but this could be due to many differences between the sites.
In conclusion, these experiments have shown that urban trees cannot be considered to all have the same cooling ability. Their effectiveness depends not only on the species of tree but also on how they are grown; to grow fastest and provide most cooling, trees need to be grown in soil which not compacted, but which is not covered by materials that are impermeable to oxygen either. However, several questions remain, which we need to answer to help other researchers and practitioners estimate reliably and readily the effectiveness of urban trees and any associated grass at providing cooling.

First, how reliable are the results for cooling obtained from our porometer measurements? Second, how effective were our trees at cooling compared with grass? Third, is there a close relationship between tree growth and cooling ability which might allow cooling performance of a tree to be estimated from its growth? Fourth, are there other ways of estimating the cooling benefits of individual trees? The rest of this chapter describes analyses of our results and in some cases short experiments which were carried out in order to try and answer these questions.

6.3 Comparative analysis of methods of measuring cooling effectiveness of urban trees

The effect of urban greenspaces in reducing the urban heat island is well researched, but the major question about their effectiveness, particularly regarding the magnitude of evapotranspirational cooling and its effects on the urban microclimate is still debatable (Souch and Souch, 1993). As mentioned in Chapter 1, the ecosystem services provided by urban trees are often estimated by models (e.g., McPherson et al., 2005; Gill et al., 2007; Nowak et al., 2008) but rarely directly measured (Shashua-Bar et al., 2009; Peters et al., 2010; Pataki et al., 2011; Rahman et al., 2011; Wang et al., 2011; Armson et al.,
The problem with many such models is that they assume that all vegetation performs in the same way and that their effect is merely proportional to their surface cover (Ennos, 2011). However, making direct measurements on trees in an urban ecosystem also presents numerous technical and logistical challenges (Peters et al., 2010), and reliable methods are needed.

The major problem with determining cooling ability is the difficulty in measuring the precise amount of water loss from trees. The easiest way would be to measure water loss using a lysimeter, but this method is only possible for grass or for small trees in pots. In our four experiments (Chapter 2 to 5) we used a leaf porometer to estimate the whole tree transpiration rate. However, porometers only take a snapshot of water loss and the results they give are difficult to scale up to the level of the whole tree. We measured sunlit leaves and to calculate instantaneous whole-tree water loss we used total leaf area: we multiplied the crown area by the leaf area index (LAI). One problem with using this approach is that not all the leaves of the tree were sunlit, so there was likely to be an overestimation. To overcome this problem our fourth experiment (Chapter 5), which investigated the effects of climate change and urbanisation, also used a third technique to measure water loss. We used sap flow gauges incorporating thermal dissipation probes to estimate whole tree water use. The relative water loss was determined by using both leaf porometer and sap flow techniques simultaneously and comparing the results obtained from the two methods.

Importantly there are two methods to calculate energy loss from porometry. One is to calculate the water loss per unit leaf area (g m\(^{-2}\) of leaf). Transpiration rates (E, mmol m\(^{-2}\) s\(^{-1}\)) of leaves can be calculated from the stomatal conductance and meteorological data.
using Fick’s law as described in Chapters 2 to 5. Thereafter, converting the results to g m⁻² s⁻¹ and multiplied by the latent heat of vapourisation, which is 2.45 kJ g⁻¹, to calculate the energy loss per unit leaf area (W m⁻²). We used water loss per unit leaf area to compare it with the sap flow per unit canopy area in Fig. 6.1. Secondly, if we multiply water loss per unit leaf area (g m⁻² of leaf) by the LAI we can calculate the water loss per unit canopy area (g m⁻² of canopy). We used the second option while calculating the energy loss per tree in our previous chapters (2 to 5) and in Fig. 6.2 and 6.3, since the total leaf area was calculated by multiplying canopy area with the LAI.

To compare the transpiration rate based on sap flow and based on porometry, both were measured at the same time. Sap flow data were collected continuously between September 7 and October 14, 2011 from eight trees of four different treatments equipped with sap flow gauges as described in Chapter 5. The sap flow data of that particular 5-10 minutes when stomatal conductance was measured for each tree were considered and converted into g tree⁻¹ hr⁻¹. The results were also converted to sap flow per unit canopy area by dividing them by the canopy area (Peters et al., 2011).

Stomatal conductance of 7 leaves of the same 8 trees from the mid crown of each tree was measured using a leaf porometer (model SC-1, Decagon Devices, Washington, USA). The stomatal conductance were measured 3 times a day (morning: 10 – 12, midday: 12 – 15, late afternoon: 15 – 17) on 7 sunny days in September, 2011. At the same time, meteorological measurements that would enable us to calculate evapotranspiration were also made. Air temperature and relative humidity were simultaneously measured in the shade, 1.5 m above the ground using a Temperature and Humidity Datalogger - CEM DT-172 (Digital meter, Darwen, Lancashire, UK). Leaf
temperatures were also recorded using the porometer at the time of measuring the stomatal conductance. Atmospheric pressure data for each measurement day were recorded from published data of the Meteorological station, Manchester Airport, UK. To check whether there was any significant difference in wind speed at the time of measurement, wind speed at 1.5 m above ground was also measured using a hand held digital anemometer (Omega digital anemometer, model HHF92A). Transpiration rate per unit leaf area (g m\(^{-2}\) s\(^{-1}\)) was calculated from stomatal conductance and meteorological data and converted to g m\(^{-2}\) hr\(^{-1}\). Finally, water loss per tree was calculated according to equation 6.1:

\[
\text{Water loss per tree} = \text{water loss per unit leaf area} \times \text{LAI} \times A \tag{6.1}
\]

where LAI is the leaf area index of the tree and A is the crown area of the tree calculated from its crown diameter. The LAI of the selected trees was also measured between 12.00 and 16.00 using an AccuPAR model LP-80 PAR/LAI Ceptometer (Decagon Devices, WA).

The transpiration rate of leaves of the same trees were also simultaneously measured on two occasions using a portable gas analyser (LCpro, ADC BioScientific Ltd, UK) while measuring the stomatal conductivity using leaf porometer. When we compared the transpiration rate measured with gas analyser and leaf porometer (model SC-1, Decagon Devices, Washington, USA), the leaf porometer showed a 5-7% overestimation in transpiration (data not shown).
6.3.1 Results and discussion

In general leaf transpiration based on the leaf porometer measurements was highest at mid-day followed by the late afternoon and morning time, whereas the sap flow was highest at mid-day followed by the morning and the late afternoon (Fig. 6.1). Transpiration rate per unit leaf area showed around 58 % overestimation compared to sap flow per unit canopy area (Fig.6.1). This is within the expected range of variation since the leaf transpiration rate is usually higher compared to the sap flow especially during the midday and afternoon (Ansley et al., 1994). However, transpiration rate per unit leaf area, which did not considered LAI, were still higher than the sap flow rate per unit canopy area which includes the density of the canopy. Therefore, when scaling up the porometer measurements by multiplying water loss by both canopy area and LAI would overestimate the whole transpiration rate by a much greater amount. This is more evident when we compare the water loss per tree based on porometer and sap flow gauges (Fig. 6.2)

![Figure 6.1: Comparison of water loss per unit area from eight young P. calleryana trees based on thermal dissipation sap flow method and leaf porometer at three times of 7 days in September, 2011.](image)
A one way ANOVA showed significant difference of the whole tree transpiration rate based on the porometer measurements at different times of the day \[ F (2, 112) = 3.109; \ p < 0.05 \]. A post hoc test showed a significantly higher water loss during mid-day and late afternoon compared to the morning based on leaf porometer. In contrast, whole tree sap flow was not significantly different at different times of the day. However, the most obvious finding was that the estimate from the sap flow gauges was less than half that from the porometer.

![Figure 6.2: Comparison of whole tree water loss from eight young *P. calleryana* trees based on thermal dissipation sap flow method and leaf porometer at three times of 7 days in September, 2011.](image)

The mean ratio of the whole tree water loss based on porometer and sap flow (Fig. 6.3) was also significantly different at different times of the day \[ F (2, 112) = 8.691; \ p < 0.001 \], a post hoc test showing that the ratio during the late afternoon was significantly higher than in the morning and mid-day.
The major finding of this research was that ignoring LAI from our calculation the estimate of instantaneous water loss using the porometer measurements showed an overestimation of around 50% compared to the sap flow. However, calculating the total leaf area of the crown by multiplying by both canopy area and LAI gave a more than two fold overestimation when we compare the water loss per tree basis. This might be due to several reasons. On the one hand, though porometers might give accurate measurements for a single leaf in the outer boundary layer, when we extrapolate the results to the canopy level, there is a good chance that we might overestimate water loss because of the light and humidity gradients within the crown (Schulze et al., 1985). Only outer leaves will receive full sunlight and be exposed to the ambient humidity, while inner leaves will be shaded and held within the cooler, damper air that results from evapotranspiration by the leaves around them. This result also indicated the fact that for calculation of evapotranspirational cooling LAI is important but we need to calculate LAI of the outer surface area of the crown and of the inner surface area separately. However, for the
calculation of the shading effect of trees it is LAI as a whole which determines how much sunlight a tree can intercept (Peters and McFadden, 2010).

On the other hand, estimation of water loss using sap flow measurements might underestimate the sap flow rate. Such underestimations of transpiration have been found by previous studies from forest ecosystems, particularly during periods of high radiation (Hogg et al., 1997; Wilson et al., 2001; Bovard et al., 2005; Oishi et al., 2008). However, this underestimation is mainly a concern for ring porous hardwood trees in which water conduction is limited to the outermost growth ring (Hacke et al., 2006; Taneda and Sperry, 2008). It is much less a problem in conifers and diffuse porous hardwoods which conduct throughout the sapwood (Peters et al., 2010; Peters et al., 2011). In addition, tree classification schemes that explain major differences in species’ water use also relate plant rooting depth with shallowly rooted trees having more stomatal regulation than deeply rooted plants (Cregg, 1994; Sobrado, 1997). There is also evidence that tree water use varies with the successional stage or shade tolerance of a tree (Abrams, 1988; Asbjornsen et al., 2007); shade intolerant species have less stomatal resistance and higher transpiration rates. Our investigated tree *P. calleryana* is a diffuse porous, deep rooted (Atkinson, 1980; Perry, 1982; Gilman et al., 1987) and shade intolerant (Culley and Hardiman, 2007) tree, which makes it less likely that the sap flow was an underestimation.

It is more likely, therefore, that the porometry measurements overestimated the water loss than that the sap flow measurements underestimated it. It seems likely that the inner leaves, being shaded, hydrated and cooled by lying behind the outer leaves, would have much lower water loss. Therefore, though when scaling up the transpiration rate of the
whole tree we multiplied the transpiration rate by both the crown area and LAI similar to the Lindsey and Bassuk (1991) model used by Sivyer et al. (1997) and we assumed that all the leaves will transpire at the same rate like those in the outer boundary layer, this is unlikely to be the case. Assuming the sap flow measurements are accurate we need to conclude that there were overestimations in our previous calculations of whole tree transpiration rate based on the porometer. Several studies agree with our findings which suggest that whole tree transpiration rate measured by a porometer and considering the total leaf area (canopy area and LAI) is much greater than that produced by sap flow or gravimetric techniques (Fichtner and Schulze, 1990; Gucci et al., 1990; Ansley et al., 1994). Fichtner and Schulze (1990) also reported that xylem flow transpiration of the vine, *Entadopsis polystachya*, was 50% of transpiration measured on abaxial leaf surfaces with a LiCor LI-1600 porometer.

Therefore, our results of energy loss per tree in chapters 2 to 5 were overestimates. Reanalysing our results in chapter 2, 3, 4 and 5 based on porometer measurements excluding LAI show that the energy losses per tree was lower than first calculated, but retained the pattern noted in the original papers. Differences between trees of different species (Fig. 6.4 a), under different rooting conditions (Fig. 6.4 b,c) and under simulated urbanized and climate changed conditions remained (Fig. 6.4 d).
Figure 6.4: Energy loss calculated a) for five different tree species grown in different streets of Manchester, UK in May and July, 2011 (Chapter 2) b) from *P. calleryana* trees grown in three different growing conditions measured during July and August, 2010 in five different streets of Manchester, UK (Chapter 3) c) from *P. calleryana* trees grown in three different pit designs measured over the summers between 2010 and 2012 (Chapter 4) d) from *P. calleryana* trees grown in four different treatments measured over the summers between 2010 and 2012 (Chapter 5).
6.3.2 Optimising methods to measure water loss

From our discussion and investigation it can be said that the leaf porometer is an excellent field instrument to calculate the instantaneous leaf level transpiration rate, though it does have limitations. It provides reliable results on stomatal characteristics, despite high leaf-to-leaf variability, a limited number of measurements (highly labour intensive) and the difficulties of crown access (Schulze and Kuppers, 1979; Turner et al., 1984). On the other hand, the measurement of sap flow is a well-proven method for continuous monitoring of whole-tree water fluxes, at least in the medium term (Granier et al., 1996; Oren et al., 1996; Andrade et al., 1998; Kostner et al., 1998; Wullschleger et al., 1998). However, due to the logistic support it needs and its vulnerability to vandalism, it is difficult to use it in urban street trees. Instead, if we can scale up the leaf transpiration rate properly it will be cheaper and easier to quantify the appropriate whole tree water loss from porometers.

Scaling up the porometer measurements to the whole canopy level from per unit leaf area, multiplying them with both canopy area and LAI would likely overestimate the total water loss. Rather, authors such as Dawson (1996), and Ansley et al. (1994) measured the total leaf area (using a destructive method) and multiplied the per unit leaf result to get the whole tree water loss. Another way would be to multiply transpiration rate per unit leaf area only with the LAI (Kjelgren and Montague, 1998) considering sunlit and shaded leaves as follows:

\[ E_{tot} = E_s \left( \frac{LAI_s}{LAI_{tot}} \right) + E_{sh} \left( \frac{LAI_{sh}}{LAI_{tot}} \right) \]
Where $E_s$ and $E_{sh}$ are the transpiration rates for sunlit and shaded portions of the canopy respectively. According to Monteith and Unsworth (1990) the sunlit leaf area $\text{LAI}_s$ can be calculated as a fraction of total $\text{LAI}_\text{tot}$ such as

$$\text{LAI}_s = \frac{(1 - e^{-k \text{LAI}})}{k}$$

Where $k$ is the transmissivity or porousness of a tree crown to light and is a function of leaf orientation relative to the ground surface and solar elevation (Kjelgren and Montague, 1998). Thus the amount of shaded leaf area is:

$$\text{LAI}_{sh} = \text{LAI}_\text{tot} - \text{LAI}_s$$

We can use this model to give a more accurate whole canopy water loss using the porometer. On the other hand, one of the major criticisms of the porometer we used (model SC-1, Decagon Devices, Washington, USA) is that it does not have an artificial ventilation system. However, according to the manufacturer’s manual if there is low to moderate wind flow (at least 1 m/s) the boundary layer resistance of the leaf is insignificant. Even porometers with artificial ventilation such as the Li-Cor LI-1600 steady state porometer can seriously overestimate water loss (Meinzer et al., 1995), because the constantly ventilated chamber of the porometer creates an abnormally high boundary layer conductance ($gb \approx 2250 \text{ mmol m}^{-2} \text{ s}^{-1}$) (Motzer et al., 2005). As discussed in Chapter 1 we can replace leaf boundary layer resistance ($gb$) by an expression introduced by McDermitt (1990):

$$gb = C (u/d)^{0.5}$$
where \( u \) is wind speed (m s\(^{-1}\)), \( d \) is mean leaf extension (m) and \( C \) is a constant (~0.24 mmol m\(^{-2}\)).

### 6.4 Comparing the cooling effectiveness of trees and grass

To compare the cooling effectiveness of trees and grasses the simplest way is to compare the water loss from them. Few studies have been carried out to investigate the cooling effectiveness of urban grasses, however, since water losses from grassland and agricultural crops can be accurately modelled using the well known Penman-Monteith model of evapotranspiration (Allen et al., 1998). Water losses from urban grasses are usually modelled simply by assuming that they behave like pasture grass (Dimoudi and Nikolopoulou, 2003; Gill et al., 2013).

The potential evapotranspiration (PET) is calculated for a well watered, non-stressed, cool season grass using the Penman-Monteith equation with an assumed crop height of 0.12 m, an albedo of 0.23, and a fixed surface resistance of 70.0 s/m (Allen et al., 1998). The term PET can be used interchangeably with the reference evapotranspiration (ET\(_0\)) (Montague et al., 2004). In order to compare PET with the energy loss from actual urban grasses and trees we performed a small scale experiment in May, 2012 inside the Botanical Grounds of the University of Manchester, UK.

#### 6.4.1 Experimental methods

Measuring water loss from grasses instantaneously is difficult as they do not have an obvious canopy or a trunk along which water flow can be measured. We developed a method of measuring the daily evapotranspirational water loss from grass by growing
grass in plastic trays and weighing those (Gill et al., 2013). Rye grass turves cut from the existing lawn were grown in 10 trays, each 65 cm long, 50 cm wide and 12 cm deep, which were buried into the grass surface. Five of the trays were buried under full sunlight and the other five underneath the constant shade of a line of lime *Tilia cordata* trees in the Botanical Grounds of the University of Manchester. The trays were weighed at 9 am and 8 pm every day between May 21 and May 29, 2012. This period was selected as those days were relatively cloudless with a higher mean air temperature (18.5 °C) compared to the mean air temperature of the rest of the month (10 °C) (http://data3.cas.manchester.ac.uk/2012/). The weight loss that occurred was a result of water loss through evapotranspiration, since there was no rain, and thus day time and night time evapotranspiration was measured. The small amount of night time dew deposition was ignored. No watering was done and therefore, grasses started to dry out towards the end of the dry spell. To compare the evapotranspiration rate with PET, PET was calculated using the ET$_0$ calculator (FAO, 2009). For the input description in the calculator, air temperature, relative humidity, wind speed, radiation data were collected from the nearest weather station, which was located on the roof of the George Kenyon Building, around 2 miles north of the experimental grounds.

To compare water loss from grass with the water loss from trees, whole day water loss from two control *P. calleryana* trees grown nearby in the Botanical Grounds (Chapter 5) were measured using sap flow gauges as previously described. Whole day water loss per tree was then divided by crown area to obtain the values in the required unit (mm day$^{-1}$) which is basically transpiration rate per unit canopy area.
6.4.2 Results and discussion

The water loss from areas of lawn in full sun was around 75% of the PET (Fig. 6.5). Water loss was greatly affected by permanent tree shading, however, which reduced evapotranspiration by a further 75%. The water loss from young *P. calleryana* trees was close to PET around half of the dry period until the drier and hotter air temperature increased PET from May 25th. Towards the end of the nine day dry period, the evapotranspiration started to fall to only around 50% of PET, showing that drought was already restricting water uptake. Interestingly, the results also showed the effect of the deep rooting system of trees, which showed that they can withstand short dry spell much better than grasses.

![Figure 6.5: Water loss from grass in sun and shade, trees per unit canopy area and potential evapotranspiration rate (PET) in the Botanical Grounds of the University of Manchester in May, 2012.](image)

Assuming that during that in this cloudless period trees and grasses were not under severe water stress conditions, the average water loss throughout these 9 days were 3.8 and 3.2 mm day\(^{-1}\) (Fig. 6.5) from trees and grasses in the sun respectively. This water
loss would provide an average cooling over a 16 hour day (assuming insignificant night time transpiration) of \(3800 \text{ ml} \times 2450 \text{ (latent heat of vapourisation J g}^{-1}\)) / (16 \times 60 \times 60) = 162 \text{ W m}^{-2} \) for trees and around 135 \text{ W m}^{-2} \) for grasses in the sun. These results, showing higher transpiration by trees, are supported by the results of Baldocchi et al. (2004), and Zhang et al. (1999) where the authors reported that fast growing tree species transpire faster than grass in moderate dry spells since they can uptake water from greater depth (>0.6m). In contrast, authors such as Offerle et al. (2006); Kotani and Sugita (2005) and Peters et al. (2011) showed that during the growing season grass can transpire more per unit area compared to both needle leaf and broadleaved tree species. Therefore, the relatively dry May of 2012 followed by the 9 cloudless dry days (between May 21 and May 29, 2012) might have reduced the water loss from grass compared to the water loss from per unit canopy area of trees in this experiment. In addition, authors such as Bartens et al. (2009) grew green ash (Fraxinus pennsylvanica Marsh.) and swamp white oak (Quercus bicolor Willd.) in structural soil and reported that both transpiration and infiltration rate increased by about 55% (oak) and 70% (ash) compared to slow infiltrated compacted growing medium. The results imply that planting suitable tree species within grass swards in less compacted sand based soil or structural soil could sum the combined cooling benefit of 135 \text{ W m}^{-2} \) and 162 \text{ W m}^{-2} \) from grasses in the sun and trees respectively to further increase cooling.

Of course, trees differ in their cooling capability, as we saw in Chapter 2. Considering the relative performance of the five different tree species (Chapter 2), therefore, and using the average energy loss from \(P. \text{ calleryana} \) (162 \text{ W m}^{-2}) during the dry spell of May, 2012 as a baseline, implies cooling of 109 \text{ W m}^{-2} \) for C. laevigata (67 % of \(P. \text{ calleryana} \)) and 81 \text{ W m}^{-2} \) for (50 % of \(P. \text{ calleryana} \)) for Malus ‘Rudolph’, Prunus
‘Umineko’ and *Sorbus arnoldiana*. Therefore, not all species will have higher energy loss compare to lawn grasses; rather fast growing tree species will lose energy faster than grass surface which is in accordance with the results found by other authors such as Zhang et al. (1999).

### 6.5 The relationship between tree growth and cooling ability

As we have seen in our series of investigations, faster growing species of trees and groups of trees of the same species that grew faster both tended to lose water faster (and hence provide more cooling) than slower-growing ones. This is not a totally unexpected result as many authors have previously found such a relationship. For example, Vertessy et al. (1995) showed that the growth rate of a tree, as measured by its dbh increment, can explain almost 88% of the variation in mean daily spring transpiration while investigating the relationships between stem diameter, sapwood area, leaf area and transpiration in 15-year-old mountain ash (*Eucalyptus regnans* F. Muell.) trees.

#### 6.5.1 Experimentally determined relationships between growth and cooling

Regression analyses of energy loss per unit area vs dbh increment on the *P. calleryana* trees that were examined in our four experiments was therefore carried out. The results (Fig. 6.6) show that in all cases faster growing trees lost significantly more energy per unit canopy area. The slopes and intercepts of the regression lines were different, but this may have been because they had grown in different conditions, for different time spans, they were of different ages (and hence dbh, height and canopy area) and their stomatal conductivity was measured at different times of the year.
Figure 6.6: Regression line between DBH increment and energy loss per unit area from *P. calleryana* trees grown in four different experiments a) Trees grown in cut-out pits in the pavements for six years (Chapter 2) b) trees grown in three different rooting conditions for six years (Chapter 3) c) trees grown in three different pit designs for three years (Chapter 4) d) trees grown in control and urbanized conditions inside the Botanical Grounds (Chapter 5).

### 6.5.2 Estimating the cooling ability of a single tree using growth rate

A simple approach to estimate the cooling ability of a single tree from its growth rate is based on the way in which plants control their water loss and the physics of the movement of gases (Ennos, 2011). The whole evapotranspiration process occurs due the opening of stomata by plants for their photosynthesis. The rate of evapotranspiration will be directly proportional to the rate at which CO₂ enters the stomata (Ennos, 2011) and the
water use efficiency (WUE) of photosynthesis in conventionally photosynthesising C$_3$
plants can be given by the equation 6.2:

$$\text{WUE} = \frac{1.6c \text{ Pa}}{(e^*\text{L} - e)}$$

(Farquhar et al., 1980; Sinclair et al., 1984). Here Pa is the ambient concentration of CO$_2$
in the atmosphere, c is 1 minus the ratio of internal to external CO$_2$ concentration ($(1 – \text{Pi} /\text{Pa})$, which is around 0.3 for conventionally photosynthesising C$_3$ plants), e$^*$L is the
saturation vapour pressure at leaf temperature and e is the vapour pressure of the atmosphere.

Studies on young poplar and Douglas fir trees (Waring et al., 1998; Ripullone 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 is
1.5 to 2.5g biomass kg$^{-1}$ water loss (Ennos, 2011). Inverting the equations provides the
following estimates for water loss per unit of above-ground biomass sequestration
(equation 6.3).

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

Since evaporation of water requires $2.45 \times 10^3$ J g$^{-1}$, it is also straightforward to calculate
the cooling provided (equation 6.4).

$$\text{Cooling} = 1.0 \text{ to } 1.6 \times 10^9 \text{ J kg}^{-1} \text{ biomass sequestered}$$
Considering the *P. calleryana* trees grown on our control plots which were used to compare the water loss with grass and PET in Fig. 6.5, we can calculate biomass sequestration (according to Guidi et al., 2008) as 0.62 kg m\(^{-2}\) yr\(^{-1}\) as follows:

Firstly, fresh volume (V) was calculated as

\[ V = H \times DBH^2 \]

Here, H is the total height and DBH is the diameter at breast height.

Then, V was divided by the age of those trees (7 years) and biomass yield per annum was calculated assuming the wood density was 0.60 g/cm\(^3\) (according to our assumption in Chapter 2). To obtain per unit value the result was then divided by 3.24 m\(^2\) (our plot size was 1.8 × 1.8 m\(^2\)).

Now, assuming a 180 day season cooling (equation 6.4) over a 16 hour day would be 1 to \(1.6 \times 10^9 / (180 \times 16 \times 60 \times 60) = 156\) to 249 W m\(^{-2}\) which is within the range of our value of 162 W m\(^{-2}\) during the short dry spell of May, 2012.

The results of the different studies, and of the theoretical calculations therefore provide some support for the theory that water cooling ability of trees could be estimated if we knew their growth rate.

### 6.6 Recommendations for further research

In order to reduce the need to make assumptions and to better quantify whole tree water loss using widely the acceptable practical methods such as leaf-porometers, sap flow
gauges and lysimeters, it is necessary to carry out some comparative investigations. The best way would be to compare the three readily available methods for comparing and scaling up, by investigating water loss from saplings growing in a 65 litre container (as supplied in our experiments: Chapter 4 and 5) using lysimeters, porometers and sap flow gauges over a certain period of time. This would allow us to make regression equations to interconvert the results of the different methods. This should be done on several tree species, so the methods have wider application. To check the variability, we could investigate large trees of the same species in urban environments, installing sap flow gauges (for example like those that Pataki et al. (2011) installed in Los Angeles, USA) and simultaneously measure stomatal conductance at different levels and depths of the crown.

As a generalization, we suggested that trees and grass planted together in sand-based or structural soil would increase cooling ability. However, it would be a good idea to investigate these assumptions by performing experimental investigations using different species and in different climatic conditions.

Our simulated climate change and urbanized experiment only investigated the effect of changes in the soil-root rhizosphere. However, as discussed in Chapter 5 changes in these conditions are highly unlikely to occur without simultaneous changes in air composition and temperature. Therefore, a greenhouse or large field experiment with increased air temperature and greenhouse gas concentration along with the urbanization and simulated climate change effect on the soil-root rhizosphere would be highly illuminating to compare our assumptions.
Finally, for model parameterization it would be very useful to experimentally investigate the evapotranspiration and hence evaporative cooling of several different micro-sites (such as streets with trees, parks, home gardens, lawns etc.) in a city and compare them with measurements of water loss using eddy-covariance techniques.

6.7 Conclusion

In conclusion we can say that in terms of cooling ability, some trees are better than others, and that growth conditions affect the cooling rate more than the species of tree. Trees grow best and provide most cooling when grown in open pits containing uncompacted soil, and when these conditions are met, energy loss per unit canopy area of fast growing species such as *P. calleryana* can be higher than that in grass lawns. Generally, fast growing tree species with higher canopy density and canopy spread have better cooling ability. There is some indication that with anticipated climate change there will be higher amount of water loss from urban trees, hence they will have greater cooling ability but this opens up the question of whether in climate change conditions, urban trees will be able to sustain their growth and vigour. More field research is needed to answer this.

We have shown that energy loss per unit leaf area from trees like *P. calleryana* can be up to 400 W m\(^{-2}\) in the month of July with plenty of soil moisture and solar irradiance. Considering the energy we receive from the sun peaks at over 800 Wm\(^{-2}\) during summer even in the UK this implies that trees such as *P. calleryana* can use up to 55% of the incoming energy as latent heat flux. In the same month, latent heat flux for the rest of the species would range between 22 – 30% of the total radiation. It is most likely that in case of *P. calleryana* the dominant energy partitioning went to latent heat flux but for the
other tree species it was sensible heat flux, because the energy balance for a plant canopy is the summation of latent heat, sensible heat and canopy heat storage and this storage is negligible (Barradas, 2000). However, our estimations do not contradict other published results that have reported a higher latent heat to incoming energy ratio; they are, rather, conservative estimations. For instance, Green (1993) reported that about 64% of the total radiant energy is absorbed by an isolated walnut tree as latent heat. Baldocchi and Vogel (1996) also reported peak rates of latent heat flux over a temperate broad-leaved forest exceed 400 W m$^{-2}$ compared to 125 W m$^{-2}$ over a jack pine boreal forest. In terms of energy partitioning, they showed that 77% of all energy was consumed as latent heat in the case of a broad-leaved forest compared to only 36% for a boreal forest.

Considering the simple energy balance equation discussed in Chapter 1

$$R = H + LE + S$$

Where, R is the net radiation, H is the sensible heat flux, LE is the latent heat flux and S is the storage, we can solve the equation for a unit area by measuring the net radiation and storage heat flux if we know latent heat flux of that unit area. We can then scale it to the mesoscale using a detailed GIS map of a city. If we know the easiest way to measure the water loss from an individual tree we can model a relationship between growth condition, species difference and age of different trees in a city with a standard tree inventory. Therefore, solving the latent heat flux of urban greenspaces depending on their growth conditions, ages and species could eventually help us to quantify the magnitude and effectiveness of greenspaces in the city in adapting them to climate change. Moreover, predicting the feedback of anticipated climate change we can plan and act accordingly for future climatic conditions.
This thesis has therefore presented results for the growth and cooling abilities of urban street trees and demonstrated how species difference, growth conditions and anticipated climate change will affect them. Together these studies can be incorporated into regional and local energy exchange models to inform urban planners to help them design sustainable and liveable cities for the future.
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Appendices
Appendix 1: Five different tree species grown in cut-out pits of the pavements in different streets of south Manchester, UK

Where possible the photos were taken from a northerly direction. The scale is provided by the yellow ruler, which represents 2m in height. The photos were taken at a distance of 10m away.

Crataegus laevigata: grown in Granville Avenue
Malus ‘Rudolph’: grown in Thorncliffe Grove
Pyrus calleryana: grown in Cringle Road
Prunus ‘Umineko’: grown in Manely Road
Sorbus arnoldiana: grown in Manely Road
Appendix 2: *P. calleryana* trees grown in three different rooting conditions in five different streets of south Manchester
Appendix 3.1 : Preparation of planting pits for planting *P. calleryana* trees in April, 2010 in the Dilworth Street.

- Digging to prepare 1.5 m² cut-out pit
- Preparing 2.8 × 1.2 m² pit with root cell
- Open pit with top soil
- Closed pit with urban soil
- Large pit with root cell
Appendix 3.2: Comparing the growth and vitality of *P. calleryana* grown in three different pit designs in September, 2012

*P. calleryana* trees in three types of pits in September, 2012

| Open pit with top soil | Closed pit with urban soil | Large pit with root cell |
Appendix 4: Experimental set up inside the Botanical Grounds of the University of Manchester, UK

Preparing the plots

Putting the soil heating cables

Plots with water collecting buckets

Trees with sap flow gauges installed in their stems