

## **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<sup>-1</sup>, 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), Kjellgren 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; Wullschlegel 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. 2010). 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](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
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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://plants.hq.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<sup>2</sup> 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).

Figure 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 CO<sub>2</sub> calculation**

Few studies have estimated CO<sub>2</sub> 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 ( $\pi r^2 h/3$ ). We choose the formula for a cylinder to estimate green volume of each tree:

$$\text{Green volume} = \pi r^2 h \quad (1)$$

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/cm<sup>3</sup> for *C. laevigata* and 0.60 g/cm<sup>3</sup> 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 CO<sub>2</sub> 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  $\mu\text{mol m}^{-2} \text{s}^{-1}$ ).

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 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 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  $\pm 1\%$ ) (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 ( $E$ ,  $\text{mmol m}^{-2} \text{s}^{-1}$ ) of leaves were finally calculated from the stomatal conductance and meteorological data using Fick's law (Lambers et al. 1998):

$$E = g_{v \text{ total}} \times (e_{\text{leaf}} - e_a) / P_a \quad (2)$$

where  $g_{v \text{ total}}$  is the total conductance to water vapour ( $\text{mmol m}^{-2} \text{ s}^{-1}$ ),  $e_{\text{leaf}}$  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 2, the transpiration rate was converted to  $\text{g m}^{-2} \text{ s}^{-1}$  and multiplied by the latent heat of vapourization, which is  $2.45 \text{ kJ g}^{-1}$ , to calculate the energy loss per unit leaf area ( $\text{W m}^{-2}$ ). Energy loss per tree was then calculated according to equation 3:

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

(3)

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, Effletrich, 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<sup>2</sup>) 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<sup>TM</sup> 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 CO<sub>2</sub> 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 CO<sub>2</sub> than *Malus* ‘Rudolph’.

Figure 2

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

### 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’.

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  $70 \pm 1.69$  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.

Figure 4

### 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.

Figure 5

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.

Figure 6

### 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.

Figure 7

### 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
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### 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.

Figure 8
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### 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
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#### 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 road side 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<sup>-1</sup> in May and July respectively. The values are comparable, if somewhat higher than our previous study (Rahman et al. 2011) where we got 1.4 and 1 kW tree<sup>-1</sup> 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-growing 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.

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Table 1(M. A. Rahman, D. Armson, A. R. Ennos)

		March	April	May	June	July	August	September	October	November
Mean temperature (°C)	2011	5.7	10.6	11.1	12.6	14.1	14.1	13.7	11.5	8.7
	1961-90	4.7	6.8	9.9	12.7	14.4	14.3	12.2	9.6	5.7
Mean rainfall (mm)	2011	42.8	40.6	114.4	84.2	93.2	111.0	132.6	122.7	84.1
	1961-90	102.1	76.7	79.4	82.6	86.2	110.1	118.2	132.4	136

Table 2 (M. A. Rahman, D. Armson, A. R. Ennos)

Species	May	July	August
<i>C. laevigata</i>	.76 ( $\pm$ .00593) <sup>c</sup>	.75 ( $\pm$ .01340) <sup>b</sup>	.76 ( $\pm$ .01051) <sup>ab</sup>
<i>S. arnoldiana</i>	.80 ( $\pm$ .00628) <sup>ab</sup>	.77 ( $\pm$ .03664) <sup>ab</sup>	.80 ( $\pm$ .00767) <sup>a</sup>
<i>Prunus</i> 'Umineko'	.78 ( $\pm$ .00563) <sup>bc</sup>	.81 ( $\pm$ .00387) <sup>ab</sup>	.73 ( $\pm$ .03433) <sup>b</sup>
<i>P. calleryana</i>	.81 ( $\pm$ .00357) <sup>a</sup>	.82 ( $\pm$ .00550) <sup>a</sup>	.81 ( $\pm$ .00598) <sup>a</sup>
<i>Malus</i> 'Rudolph'	.79 ( $\pm$ .00462) <sup>ab</sup>	.81 ( $\pm$ .00655) <sup>ab</sup>	.82 ( $\pm$ .00627) <sup>a</sup>

\* Figures in parenthesis are the standard errors of means

\*\* Means with the same letter were not significantly different as determined by two ways ANOVA ( $P < 0.05$ ).

Table 3 (M. A. Rahman, D. Armson, A. R. Ennos)

Species	Nutrients														
	Mean (%)					Mean ( $\mu\text{g/g}$ )									
	N	P	K	Ca	Mg	Al	B	Co	Cu	Fe	Mn	Mo	Na	Ni	Zn
<i>C. laevigata</i>	2.32 <sup>b</sup>	0.21 <sup>ab</sup>	1.03	2.32	0.21	45.30 <sup>ab</sup>	31.20 <sup>b</sup>	0.60	7.00	136.40 <sup>a</sup>	26.80 <sup>b</sup>	0.50	238.30 <sup>bc</sup>	1.70	27.20 <sup>a</sup>
<i>s. arnoldiana</i>	1.83 <sup>c</sup>	0.30 <sup>a</sup>	1.38	1.94	0.19	53.50 <sup>a</sup>	22.90 <sup>b</sup>	0.50	5.80	133.60 <sup>ab</sup>	125.50 <sup>a</sup>	3.00	242.40 <sup>bc</sup>	2.50	12.90 <sup>b</sup>
<i>Prunus 'Umineko'</i>	2.82 <sup>a</sup>	0.30 <sup>a</sup>	1.03	2.39	0.30	29.20 <sup>bc</sup>	56.80 <sup>a</sup>	0.50	5.80	76.10 <sup>ab</sup>	37.70 <sup>b</sup>	0.20	397.50 <sup>a</sup>	1.80	12.50 <sup>b</sup>
<i>P. calleryana</i>	1.81 <sup>c</sup>	0.22 <sup>ab</sup>	1.53	2.49	0.28	19.50 <sup>c</sup>	30.60 <sup>b</sup>	0.60	8.00	66.30 <sup>b</sup>	19.20 <sup>b</sup>	2.10	222.70 <sup>c</sup>	3.80	38.90 <sup>a</sup>
<i>Malus 'Rudolph'</i>	1.32 <sup>d</sup>	0.15 <sup>b</sup>	1.11	2.63	0.26	36.70 <sup>abc</sup>	37.50 <sup>b</sup>	0.40	6.50	112.60 <sup>ab</sup>	35.20 <sup>b</sup>	0.00	369.00 <sup>ab</sup>	3.40	12.10 <sup>b</sup>

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

Figure 1 (M. A. Rahman, D. Armson, A. R. Ennos)

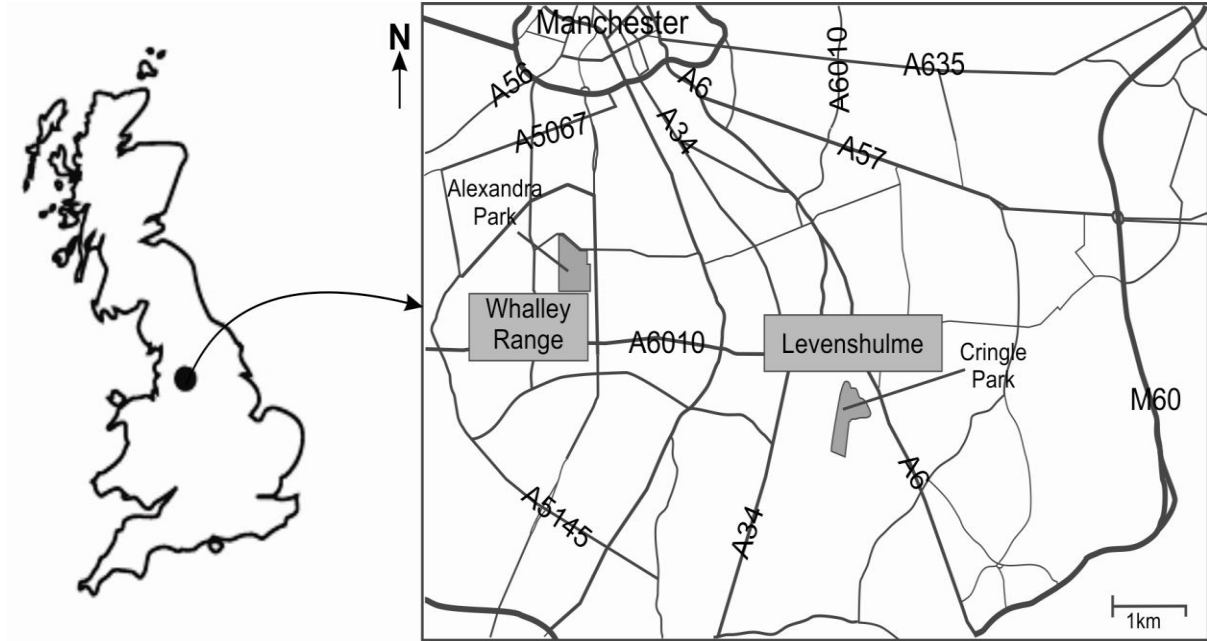


Figure 2 (M. A. Rahman, D. Armson, A. R. Ennos)

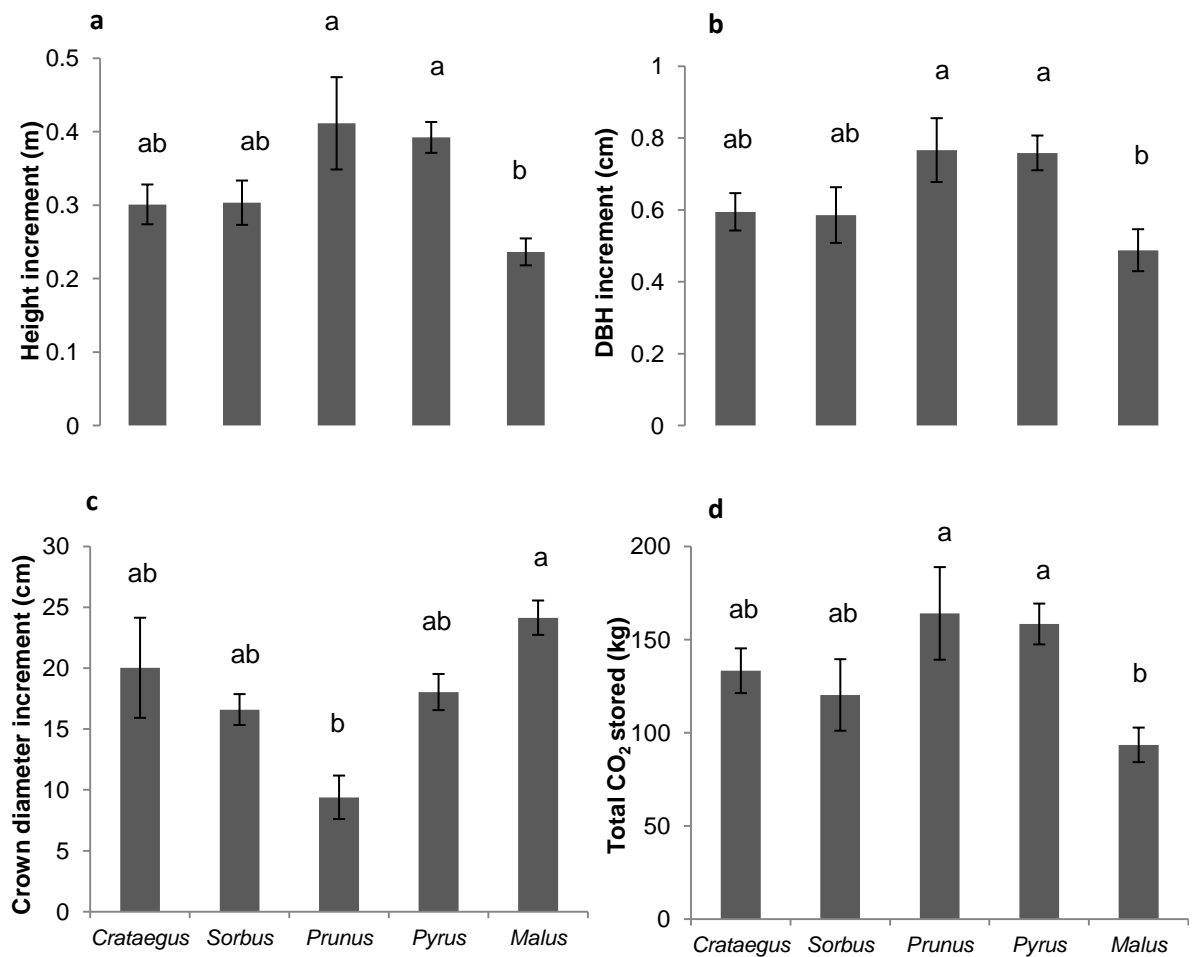


Figure 3 (M. A. Rahman, D. Armson, A. R. Ennos)

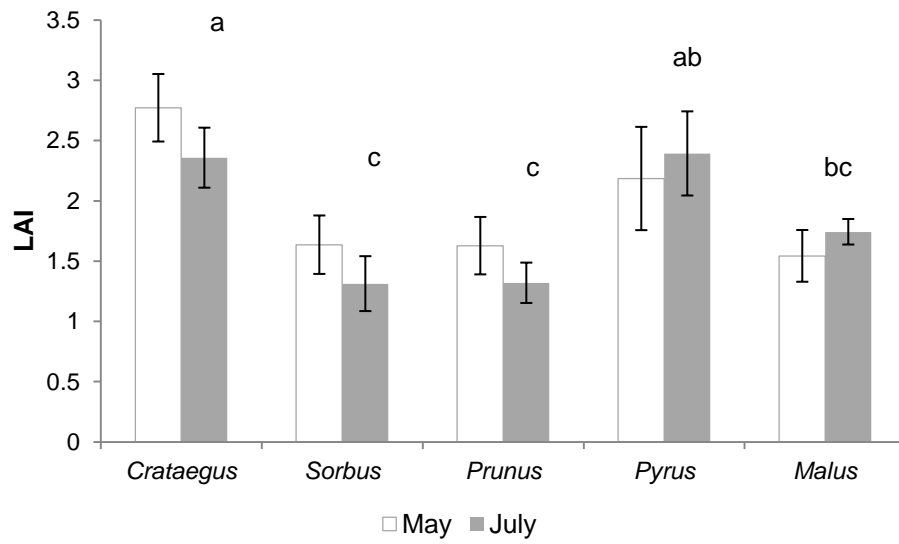


Figure 4 (M. A. Rahman, D. Armson, A. R. Ennos)

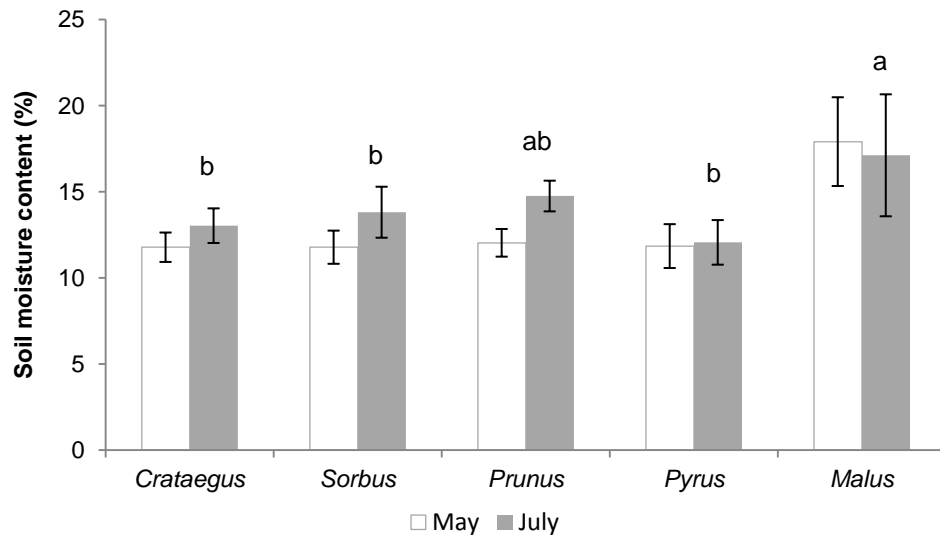




Figure 5 (M. A. Rahman, D. Armson, A. R. Ennos)

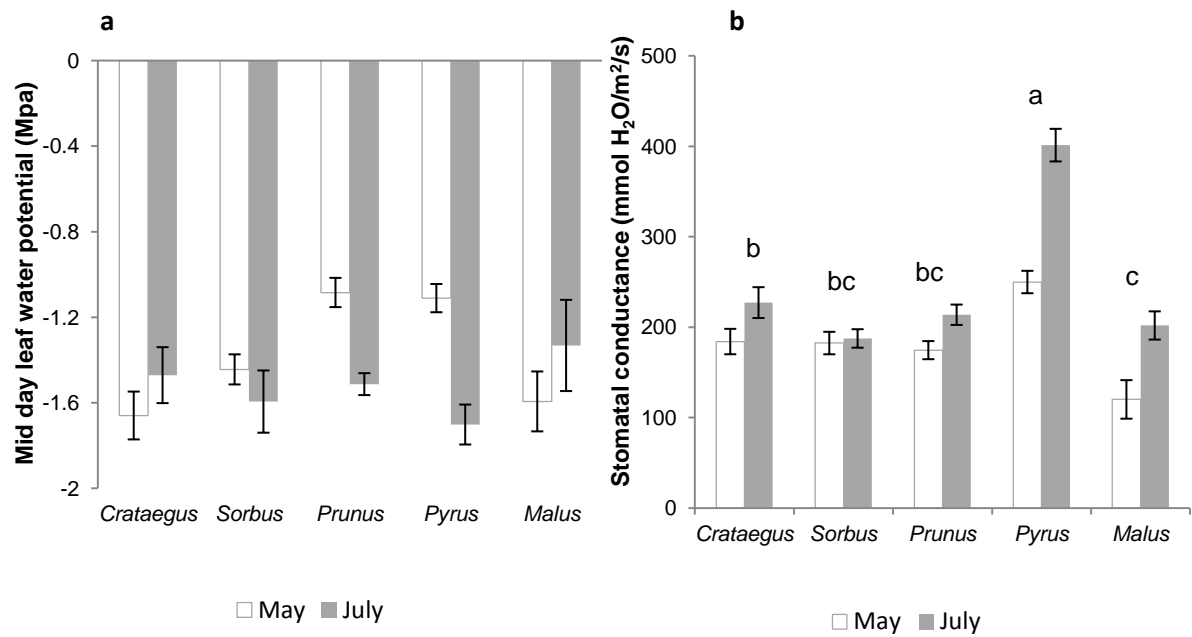


Figure 6 (M. A. Rahman, D. Armson, A. R. Ennos)

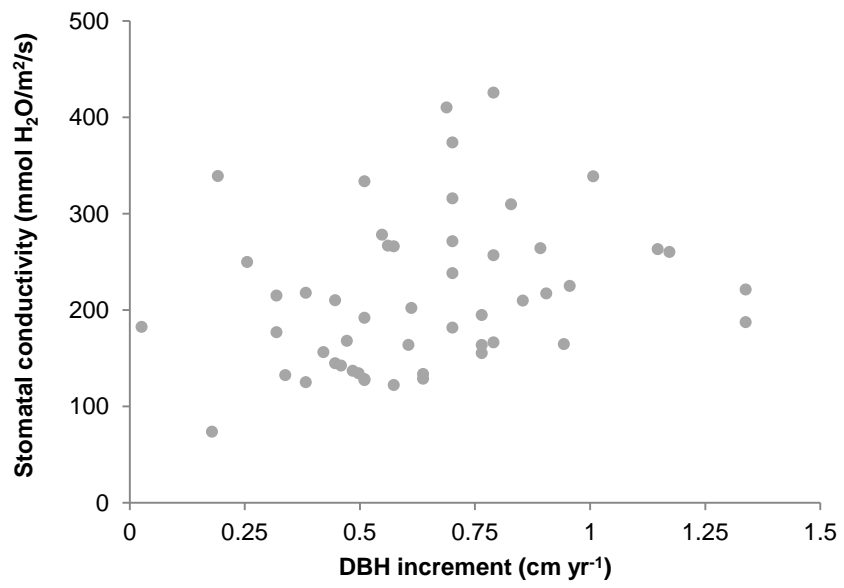


Figure 7 (M. A. Rahman, D. Armson, A. R. Ennos)

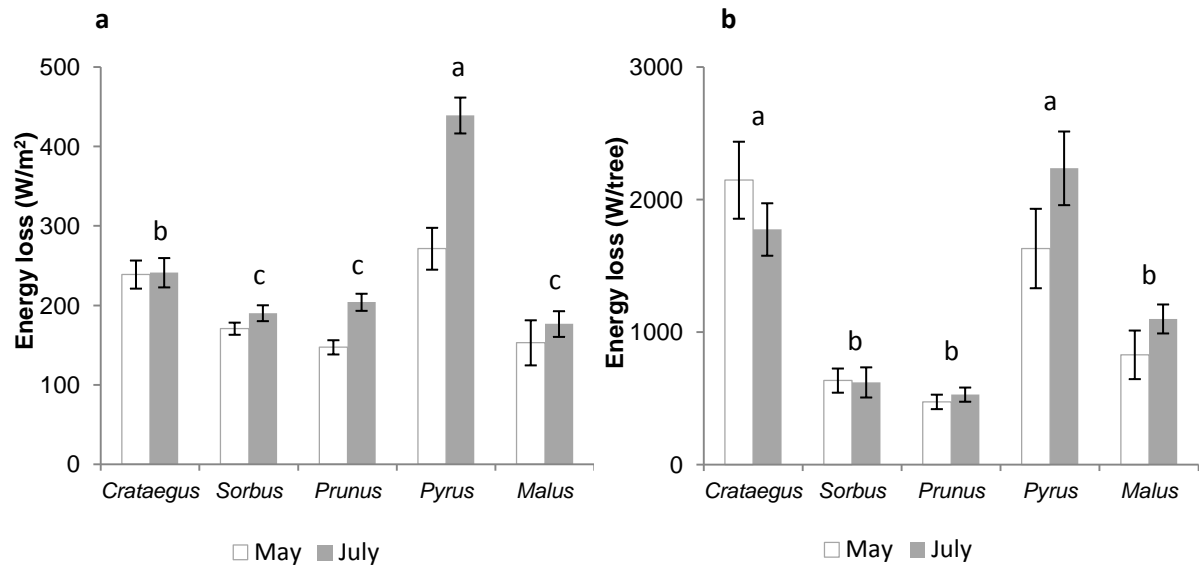


Figure 8 (M. A. Rahman, D. Armson, A. R. Ennos)

