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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 urbanization 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.

Introduction

The creation of the urban heat island (Graves et al., 2001; Wilby, 2003) and the role of urban trees in adapting our cities to urban heat island are 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; Cochard 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, 2013). 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

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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, IL, USA showed that 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 al., 2009). 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 *P. 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.

Methods

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 $< \pm 0.2$ °C from 0 °C 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 metre (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 *P. calleryana* trees, we used a randomized block factorial experiment in a plot 15 m × 7.5 m. The total area was split into 20 (1.8 m × 1.8 m) plots. 20 *P. calleryana* trees of 14–16 cm at 1 m stem height were planted in April 6, 2010 and were assigned randomly to one of four treatments; control (ON), urbanized (UN), climate change (OC), and urbanized 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 mm × 900 mm open space around the tree bases. To test uniformity, the soil shear strength was measured using a shear vane metre (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 to 2–3 °C (following the assumption of Roderfeld et al., 2008) using soil heating cables. Authors such as Ooi 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, author such as Byrne (2006) has 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 1961–1990).

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