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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 7 kW, 5 times higher than those grown in pavements.

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., 2010). 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., 1996a, 1996b; 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 m^2 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

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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. (1996a, 1996b) also compared the growth and phenology of sugar maple (*Acer saccharum* Marshall) 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, *Pyrus calleryana*, growing in the UK after a longer period of time (5–6 years).

Methods

Site selection and P. 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.

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 m^2 cut-out pits in pavements, in grass verges, and in 1.5 m^2 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 m × 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.

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. (1996b) at the initiation of bud burst, initiation of colour change, peak colour and 100% leaf fall.

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.

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-μm sieve. Total N was determined by dry combustion method using LECO TruSpec^{TM} 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).

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.

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

	February	March	April	May	June	July	August	September	October	November
Mean temperature (°C)	1.7	5	7.9	9.8	14.2	15.2	14	13	9.5	4.3
Mean rainfall (mm)	57.2	82.8	34.6	38.1	40.2	165.9	82.9	154.1	116.3	131.3

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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^{TM} 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).

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):

$$E = g_{\text{v total}} \times \frac{(e_{\text{leaf}} - e_{\text{a}})}{P_{\text{a}}} \qquad (1)$$

where $g_{\text{v total}}$ 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 Eq. (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 Eq. (2):

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

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

Statistical analysis

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

Results

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 [$F(2, 46) = 14.873$; $p < 0.001$]; in DBH increment [$F(2, 46) = 75.052$; $p < 0.001$]; in crown diameter increment [$F(2, 46) = 21.517$; $p < 0.001$]; and in LAI [F $(2, 45) = 47.577$; $p < 0.001$]. Post hoc analyses showed significant differences between all three groups in all four characteristics.

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 [$F(2, 138) = 22.523$; $p < 0.001$], and between the growing years [$F(2, 138) = 9.055$; $p < 0.001$]; 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 Amesterdam soil and grass verges was significantly higher than that of the paved streets. It also showed that the growth rate was signficantly lower in 2009–10 and 2008–09 compared to 2007–08.

Trees grown in Amsterdam soil and grass verges broke bud around a week earlier, between 26 and 28th March, 2010, compared to 6–7th 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.

Soil shear strength and relationship with the growth parameters

There were significant differences between the soil shear strength in the three different planting regimes [$F(2, 46) = 20.734$; $p < 0.001$]. 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). 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 ($R = -0.574$, $p < 0.001$) and on LAI ($R = -0.624$, $p < 0.001$). Trees grown on less compacted soil showed a higher growth and greater LAI.

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 [$F(2, 14) = 3.679$; $p \leq 0.05$] in the top 20 cm. However, no significant difference was found at 80 cm.

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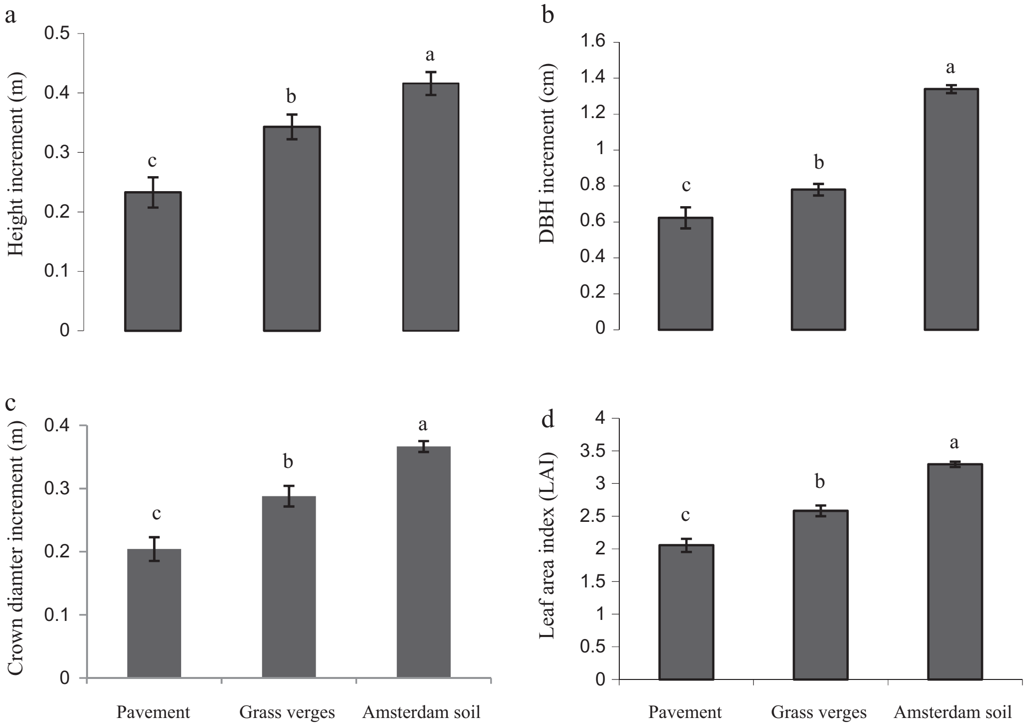

Fig. 1. Differences in growth and morphology of *P. calleryana* grown on three different planting regimes. Annual growth increments (2004–10) in (a) height, (b) DBH and (c) crown diameter and (d) LAI of the crown in May 2010. Graphs show means ± standard error ($n = 15$ for paved streets, 21 for grass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

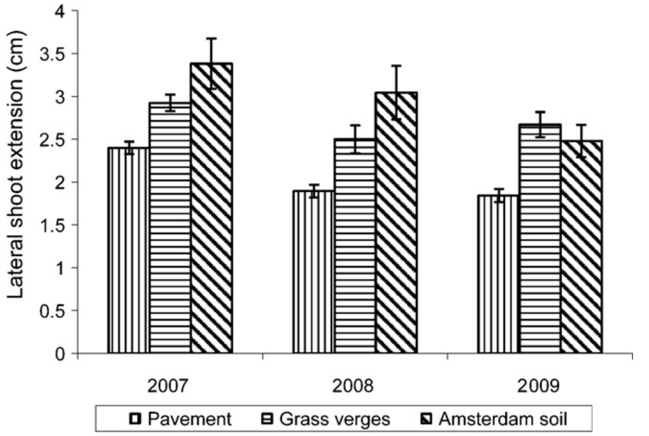

Fig. 2. Annual lateral shoot extension in the previous three years (2007–09) of *P. calleryana* grown in different planting regimes. Graphs show means ± standard error ($n = 15$ for paved streets, 21 for grass verges and 13 for Amsterdam soil).

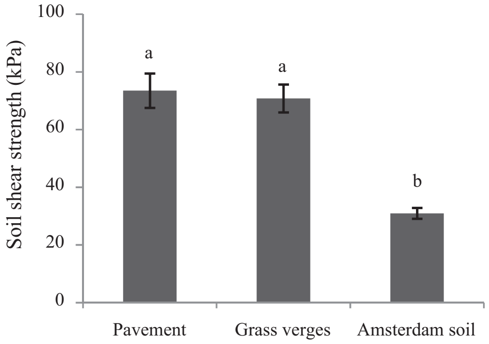

Fig. 3. Shear strength of soil around *P. calleryana* trees grown in different planting regimes. Graphs show means ± standard error ($n = 15$ for paved streets, 21 for grass verges and 13 for Amsterdam soil).

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

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.

Growing conditions	Bud break		Autumn colour and leaf fall							
	4th week of March	1st week of April	1st week of September		4th week of September	2nd week of October	4th week of October	1st week of November	3rd week of November	1st week of December
Pavements	Not started	Started	Autumn colour	10%	25%	45%	Peak			
			Leaf fall					30%	>80%	Completed
Grass verges	Started	>60%	Autumn colour	5%	10%	20%	30%	Peak		
			Leaf fall						>70%	>95%
Amsterdam soils	Started	>70%	Autumn colour	Started	10%	15%	30%	Peak		
			Leaf fall						>60%	>95%

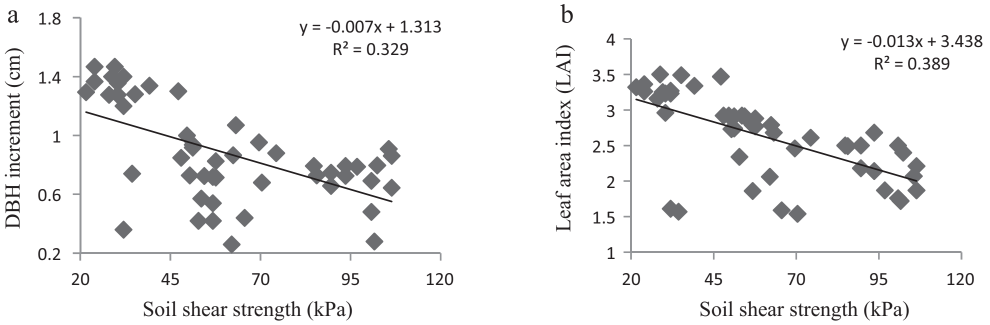

Fig. 4. Effect of soil shear strength on the growth and morphology of *P. calleryana* (a) diameter growth and (b) LAI increase.

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.

Planting regimes	Nutrients														
	Mean (%)					Mean (µg/g)									
	N	P	K	Ca	Mg	Al	B	Co	Cu	Fe	Mn	Mo	Ni	Zn	Na
Pavements	1.81	0.11	0.99	1.72	0.27	42.5	39.40	0.00	7.80	93.70	13.80	5.70	2.30	27.70	200.80
Grass verges	2.38*	0.17*	1.07	1.79	0.27	45.44	35.94	0.00	9.63	93.67	13.25	3.00	2.19	36.63	177.75
Amsterdam soil	2.39*	0.12*	1.12	1.74	0.27	51.80	64.40*	0.10	9.90	99.90	32.40**	6.10	3.90	35.70	324.10**

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

[$F(2, 15) = 4.075$; $p < 0.05$; $F(2, 15) = 6.613$; $p < 0.01$; $F(2, 15) = 8.325$; $p < 0.01$].

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 [$F(2, 17) = 15.439$; $p < 0.01$].

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.

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.

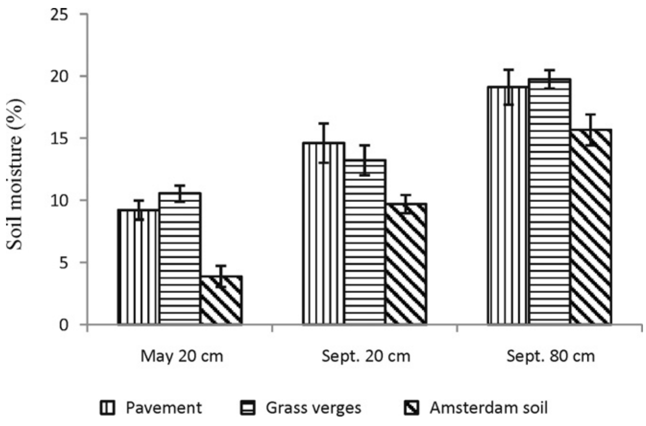

Fig. 5. Soil moisture content in the top 20 cm and at 80 cm depth around the bases of *P. calleryana* trees grown in different planting regimes. Graphs show means ± standard error ($n = 15$ for paved streets, 21 for grass verges and 13 for Amsterdam soil for 20 cm depth and $n = 6$, 6 and 5 respectively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

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.

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.

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Table 4
Nutrient status of the three growth media.

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

** Significant difference at 0.01 level.

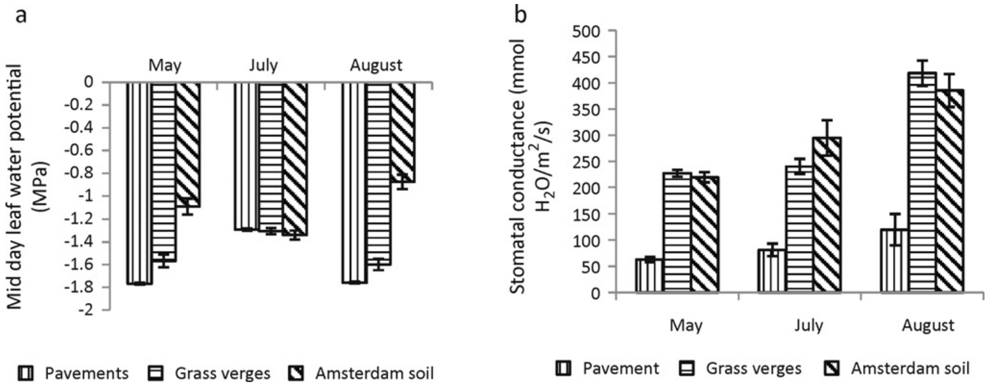

Fig. 6. Leaf physiological parameters of *P. calleryana* trees grown in different planting regimes at three different times of the year (May, July and August, 2010): (a) midday leaf water potential; (b) stomatal conductance. Graphs show means ± standard error (*n* = 15 for paved streets, 21 for grass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

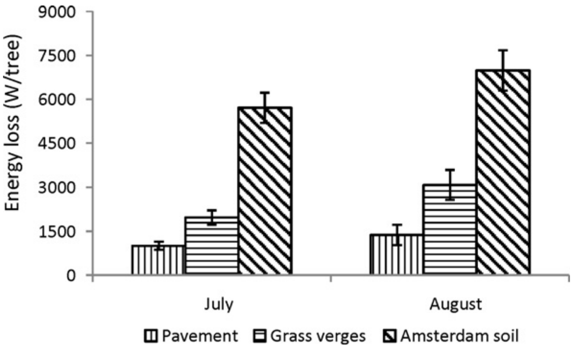

Fig. 7. Evapotranspirational cooling calculated for *P. calleryana* trees growing in three different planting regimes (*n* = 15 for paved streets, 21 for grass verges and 13 for Amsterdam soil).

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., 1996b; 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., 1996a, 1996b; Gomez et al., 2002; Grabosky et al., 2009) and nutrient uptake (Smiley et al., 1985; Close et al., 1996b) 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

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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 $\mathrm{W\,m^{-2}}$ in July and 335 $\mathrm{W\,m^{-2}}$ 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 $\mathrm{W\,m^{-2}}$. 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 $\mathrm{W\,m^{-2}}$ for an adequately watered reference crop ($\mathrm{ET_0}$) (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 $\mathrm{W\,m^{-2}}$ 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 $\mathrm{m^2}$ 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 $\mathrm{m^2}$ 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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