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# Transpiration of urban trees and its cooling effect in a high latitude city

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**Abstract**  An important ecosystem service provided by urban trees is the cooling effect caused by their transpiration. The aim of this study was to quantify the magnitude of daytime and night-time transpiration of common urban tree species in a high latitude city (Gothenburg, Sweden), to analyse the influence of weather conditions and surface permeability on the tree transpiration, and to find out whether tree transpiration contributed to daytime or nocturnal cooling. Stomatal conductance and leaf transpiration at day and night were measured on mature street and park trees of seven common tree species in Gothenburg: *Tilia europaea*, *Quercus robur*, *Betula pendula*, *Acer platanoides*, *Aesculus hippocastanum*, *Fagus sylvatica* and *Prunus serrulata*. Transpiration increased with vapour pressure deficit and photosynthetically active radiation. Midday rates of sunlit leaves ranged from less than 1 mmol m$^{-2}$ s$^{-1}$ (*B. pendula*) to over 3 mmol m$^{-2}$ s$^{-1}$ (*Q. robur*). Daytime stomatal conductance was positively related to the fraction of permeable surfaces within the vertically projected crown area. A simple estimate of available rainwater, comprising of precipitation sum and fractional surface permeability within the crown area, was found to explain 68 % of variation in midday stomatal conductance. Night-time transpiration was observed in all studied species and amounted to 7 and 20 % of midday transpiration of sunlit and shaded leaves, respectively. With an estimated night-time latent heat flux of 24 W m$^{-2}$, tree transpiration significantly increased the cooling rate around and shortly after sunset, but not later in the night. Despite a strong midday latent heat flux of 206 W m$^{-2}$, a cooling effect of tree transpiration was not observed during the day.

## Introduction

Trees have been shown to effectively mitigate heat stress in urban areas by providing shade and converting solar radiation to latent heat flux through transpiration (Mayer et al. 2009; Bowler et al. 2010; Hamada and Ohta 2010; Shashua-Bar et al. 2011). With most of the ground covered by impervious materials, tree transpiration can be the main source of latent heat flux in a built-up environment. However, in order to provide a cooling effect, urban trees need to remain healthy in spite of harsh growing conditions and stress factors absent or less severe in their natural habitats (Roberts 1977; Sieghardt et al. 2005). Knowledge about the transpiration rates of urban trees and how these depend on different environmental factors is essential for estimating the cooling effect provided by urban greenery as well as for appropriate urban planning and management to promote this ecosystem service.

Transpiration of trees is controlled mainly by the evaporative demand of air, soil water supply and the stomatal control of water loss, which differs among species (Chapin et al. 2011). Street trees surrounded by hot, impervious surfaces are exposed to high evaporative demand (Clark and Kjelgren 1990; Whitlow et al. 1992; Kjelgren and Montague 1998; Ferrini and Baietto 2007) and often suffer from poor infiltration of rainwater into the soil, which can constrain their transpiration (Sæbø et al. 2003; Nielsen et al. 2007; Chen et al. 2011). However, while transpiration of trees in natural habitats has been widely studied, little research has been conducted on the transpirational cooling effect of mature urban trees.

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Several studies were conducted on trees planted in containers (Kjelgren and Montague 1998; Hagishima et al. 2007; Bartens et al. 2009) and, although they provide valuable information about the effects of specific treatments on tree transpiration, their results may not apply for mature street trees. Other studies of urban trees have focussed on park trees (Chen et al. 2011; Wang et al. 2012), which face very different challenges from those of street trees with respect to water economy. Within the street or plaza environment, trees growing over paved surfaces were found to have restricted growth and reduced gas exchange in comparison to those surrounded by grass or bare soil (Celestian and Martin 2005; Ferrini and Baietto 2007).

Transpiration in darkness is often assumed to be negligible due to stomatal closure. However, several studies have reported non-negligible night-time stomatal conductance and transpiration of trees in natural stands (Snyder et al. 2003; Daley and Phillips 2006; Fisher et al. 2007) and urban parks (Chen et al. 2011). According to a review by Caird et al. (2007), night-time transpiration rates of various plants, including trees, usually amount to 5–15 % of the daytime values. While not directly measured, evening evapotranspiration has also been suggested by Lindén (2011) and Holmer et al. (2013) as a reason behind intensive nocturnal cooling of densely vegetated areas in the tropical city of Ouagadougou, Burkina Faso. The rapid cooling of vegetated areas in Ouagadougou around sunset, in the so-called Phase 1 of nocturnal cooling (Holmer et al. 2007), was accompanied by an increase of specific humidity not observed at non-vegetated sites, which cooled more slowly. In Phase 2, starting around 2–3 h after sunset, the cooling was less intensive, with small differences in cooling between vegetated and non-vegetated sites. Nocturnal cooling rates are of high importance in urban climate studies, as an enhanced cooling in Phase 1 can lead to lower night-time air temperature, providing a relief from heat during heat waves and decreasing heat-related mortality in urban areas (Rocklöv et al. 2011). To the best of our knowledge, there has been no study to assess the influence of night-time transpiration on nocturnal cooling in temperate climate cities.

The aims of this study were to (i) quantify the magnitude and diurnal variations of transpiration of the most common urban tree species in Gothenburg, Sweden; (ii) analyse the influence of meteorological conditions and surface permeability on the transpiration of urban trees and (iii) find out whether transpiration of urban trees contributes to daytime or nocturnal cooling.

## Materials and methods

### Study area and the site selection

The study was conducted in Gothenburg (57°42′N, 11°58′E), the second largest city in Sweden, with a population of around 540,000. The city is located in the maritime temperate climate zone, with mean air temperature of 17.0 °C in July and −1.1 °C in February and mean annual precipitation of 758 mm (SMHI 2013). There are many green areas in Gothenburg, but street trees are rather scarce, particularly in the oldest, central parts of town. Deciduous trees, which are dominant in the city, usually foliate in late April to early May and defoliate mostly in October.

Seven of the most common street tree species in Gothenburg were chosen for the study: *Tilia europaea* (common lime), *Quercus robur* (English oak), *Betula pendula* (Silver birch), *Acer platanoides* (Norway maple), *Aesculus hippocastanum* (Horse chestnut), *Fagus sylvatica* (European beech) and *Prunus serrulata* (Japanese cherry). For each species, an urban site with three to six tree individuals of similar age and dimensions was chosen (Table 1). The selected trees were mature and did not have visual signs of damage or disease. The study sites were characterized by different planting conditions, typical for an urban environment—small pits with a compacted soil surrounded by pavement, grass lawns of different width along streets or buildings and urban parks. According to personal communication with gardeners and landowners, none of the sites received irrigation. In case of *T. europaea*, the most abundant tree species in Gothenburg, three study sites were chosen—one site located in a park (cemetery) as well as two sites along streets with different traffic intensity and lawn width. Location of the study sites across the city and photographs of the studied trees are shown in Figs. 1 and 2, respectively.

### Transpiration measurements

Stomatal conductance ($g_s$, mmol m$^{-2}$ s$^{-1}$) and transpiration rate ($E_L$, mmol m$^{-2}$ s$^{-1}$) per unit one-sided leaf area as well as photosynthetically active radiation (PAR, μmol m$^{-2}$ s$^{-1}$) were measured using a Li-Cor LI-6400XT Portable Photosynthesis System (LI-COR Biosciences, Lincoln, USA) with a transparent leaf chamber. LI-6400XT is an open system measuring gas exchange between leaf and air using an infrared gas analyser. Gas exchange was measured under ambient air temperature and humidity, with a $CO_2$ mole fraction of 400 μmol mol$^{-1}$.

The measurements were conducted during daytime (around the time of solar noon, i.e. UTC+1) and night-time (1–4 h after sunset) on warm summer days of 2012–2013 (Table 2). Measurements of street trees *T. europaea*, *Q. robur*, *B. pendula*, *Aesculus hippocastanum* and *P. serrulata* were conducted on 2 days at each site, with 1 day cloud-free and 1 day with low to moderate cloudiness. Due to weather conditions and instrument unavailability, measurements of *Acer platanoides*, *F. sylvatica* and *T. europaea* park trees were only conducted on 1 day. Daytime measurements of *Q. robur* on 28

**Table 1** Description of study sites. The species are listed in order of decreasing relative abundance in Gothenburg

| Species | Street or park name | Number of studied trees | Planting regime | Mean tree height [m] | Mean trunk diameter at breast height [cm] | Vertically projected tree area [m²] | Fraction of permeable surfaces within the projected tree area | Mean leaf area index, LAI [m² m⁻²] |
|---|---|---|---|---|---|---|---|---|
| _Tilia europaea_ (common lime) | Stampen (park) | 6 | Grass lawn in a park, trees planted along alleys | 15.6±2.6 | 52±10 | 196±41 | 0.79 | 4.3 |
| | Ullevigatan | 5 | Narrow lawn along a heavy traffic road | 8.8±1.3 | 21±4 | 33±12 | 0.46 | 2.5 |
| | St Sigfridsgatan | 6 | Wide grass lawn along a street | 10.2±0.7 | 25±1 | 54±7 | 0.80 | 4.8 |
| _Quercus robur_ (English oak) | Vikingsgatan | 6 | Wide grass lawn along a heavy traffic road | 7.3±0.3 | 16±1 | 20±3 | 1.00 | 5.4 |
| _Betula pendula_ (Silver birch) | Standargatan | 6 | Pits with grass along a street | 15.1±0.9 | 19±8 | 42±13 | 0.48 | 6.5 |
| _Acer platanoides_ (Norway maple) | Såggatan | 4 | Wide grass lawn along a street | 8.2±0.6 | 12±9 | 34±4 | 1.00 | 5.5 |
| _Aesculus hippocastanum_ (Horse-chestnut) | Kungstorget | 6 | Small pits with bare soil, no grass | 11.9±1.0 | 45±6 | 87±8 | 0.14 | 5.0 |
| _Fagus sylvatica_ (European beech) | Trädgårds-föreningen (park) | 3 | Grass lawn in a park | 10.1±1.3 | 14±14 | 61±17 | 1.00 | 7.8 |
| _Prunus serrulata_ (Japanese cherry) | Mölndalsvägen | 5 | Wide grass lawn near a building | 5.8±0.7 | 69±7 | 38±5 | 1.00 | 3.6 |

**Fig. 1** Location of the
measurement sites across the city:
(*a–c*) *T. europaea* in Stampen
park and along two streets—
Ullevigatan and St Sigfridsgatan,
respectively; (*d*) *Q. robur*; (*e*)
*B. pendula*; (*f*) *Acer platanoides*;
(*g*) *Aesculus hippocastanum*; (*h*)
*F. sylvatica*; (*i*) *P. serrulata*
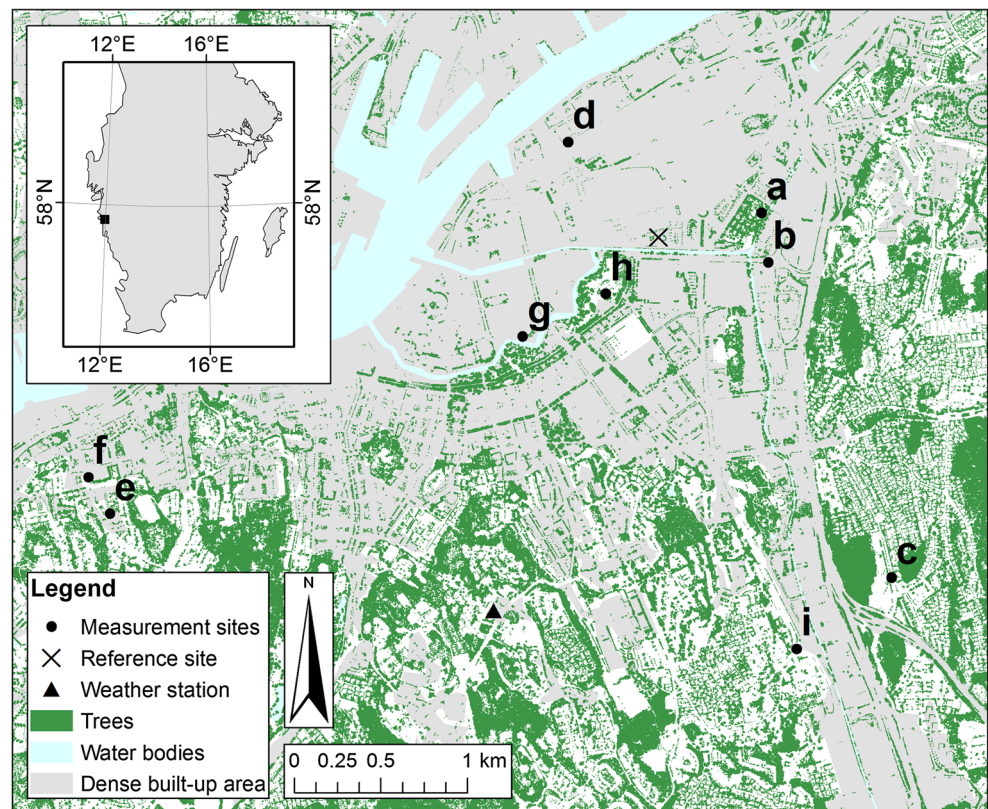


August were conducted with a few hours delay caused by
instrument malfunction.

$E_L$ was measured at low crown level, at the height of around
2 m. Since the selected trees were well exposed to sunlight,
measurements at this height could be made on fully sunlit leaves.
During each round of measurements at a site, four leaves per tree
were measured: two fully sunlit and two shaded leaves during
daytime. To analyse the diurnal variation of transpiration of street
and park trees in more detail, measurements of *T. europaea* (at
three different study sites) and *F. sylvatica* were conducted every
hour from noon until a few hours after sunset. Due to time con-
straints, during these measurements, the number of studied trees
was limited to three, except for the first and the last round of
hourly measurements.

Leaf area density (one-sided foliage area per unit canopy vol-
ume, LAD, m$^{-1}$) of the studied trees was measured using a LAI-
2200 Plant Canopy Analyzer (LI-COR Biosciences, Lincoln,
USA) and recomputed in FV2200 v. 1.2 software, following
guidelines for isolated canopy measurements provided in the
instrument manual (LI-COR 2009). The instrument estimates
the amount of foliage by a measurement of solar radiation below
and above the canopy, and a model of radiative transfer in plant
canopies. Solar radiation (320–490 nm) is measured by a fish-
eye optical sensor, at five angles from 7° to 68° from the zenith.
To avoid disturbance by adjacent trees or buildings, measure-
ments were conducted with a 45° view cap covering the sensor.

To calculate mean one-sided leaf area per unit ground area (leaf
area index, LAI), LAD was multiplied by crown volume (*V*) and
divided by vertically projected crown area (*A*) both estimated in
FV2200 software based on field measurements and photograph
analysis:

$$\text{LAI} = \text{LAD} \times \frac{V}{A} \qquad (1)$$

It should be noted that due to difficulties in photograph
analysis, caused by the crowns of the studied trees being partly
obscured by other trees growing in their vicinity, the estimated
LAI of *F. sylvatica* park trees may be overestimated.

The ratio of sunlit to shaded leaves was estimated in order
to scale up daytime $E_L$ values. Assuming a random leaf angle
distribution, which is common in broadleaf tree species (Chen
et al. 1997), and an isolated, spherical tree crown, the area of
sunlit leaves (LAI$_{sun}$) is $\sqrt{2}$ larger than the projected crown
area. Mean sun altitude on each measurement day ($\theta$) and a
simplified spheroidal crown model were used to account for
varying tree shapes:

$$\text{LAI}_{sun} = \sqrt{2} \times A_\theta/A = \sqrt{2} \times [\pi \times r \times (h \times \cot\theta)]/(\pi \times r^2) \quad (2)$$

where $A_\theta$ is the projected canopy area at the given sun altitude,
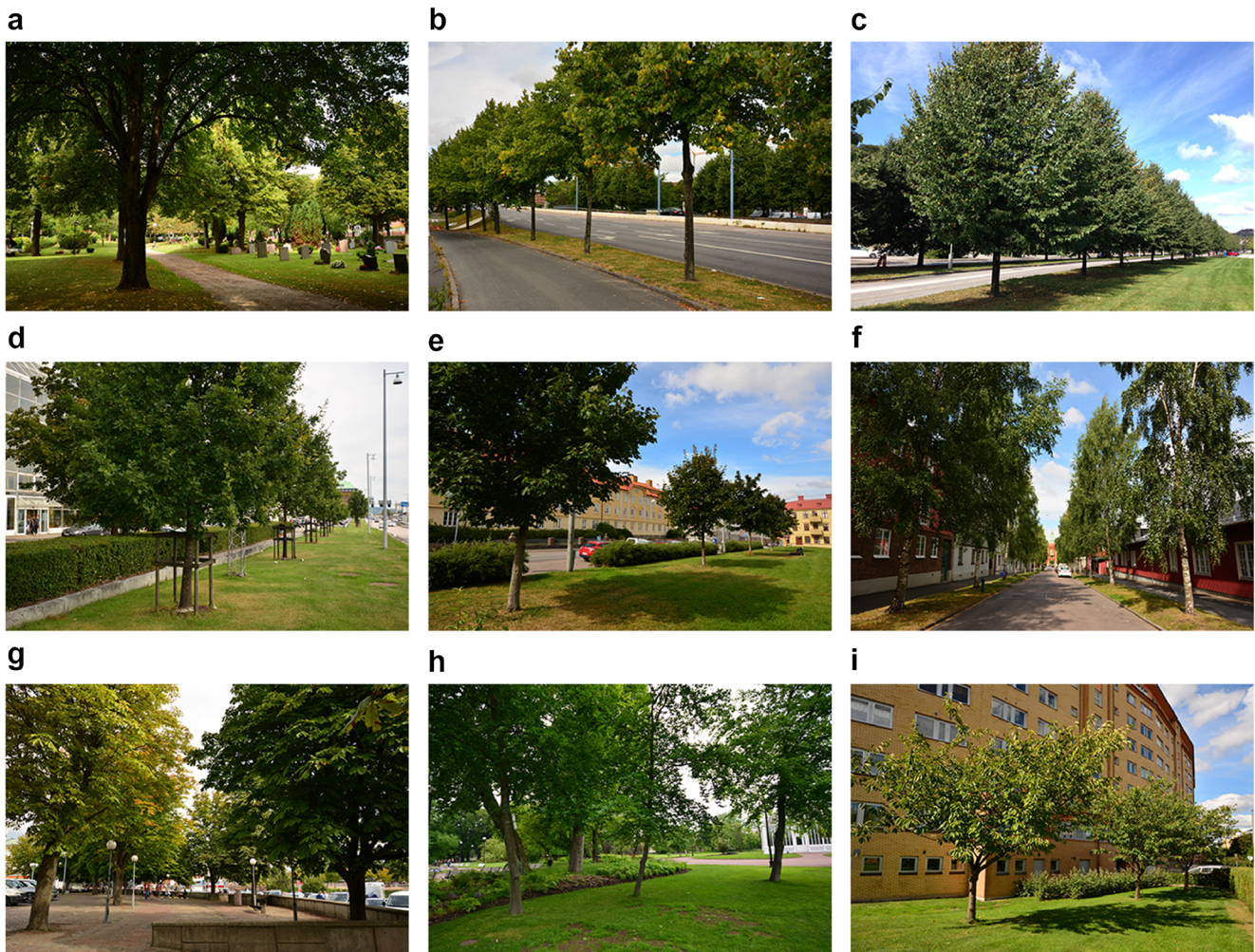while *r* and *h* are the tree crown radius and height,
respectively.

**Fig. 2** Photographs of the studied trees, labelled according to Fig. 1

The estimated ratio of sunlit to shaded leaves for different trees and measurement days ranged from 1:0.3 (low solar angle, low LAI) to 1:5 (high solar altitude, tall trees with high LAI), with an average of 1:2 (not shown). Transpiration per unit of vertically projected tree crown area ($E_G$, mmol m$^{-2}$ s$^{-1}$) was then calculated by scaling up $E_L$ using the obtained LAI$_{sun}$ and LAI$_{shade}$ values:

$$E_G = E_{L\ sun} \times LAI_{sun} + E_{L\ shade} \times LAI_{shade} \qquad (3)$$

Energy loss per unit ground area ($Q_E$, W m$^{-2}$) due to tree transpiration, i.e. latent heat flux, was calculated by multiplying $E_G$ by the latent heat of vaporisation ($\lambda$, 44.1 J mmol$^{-1}$ at 20 °C; values of $\lambda$ at the measured air temperature were used):

$$Q_E = E_G \times \lambda \qquad (4)$$

**Meteorological data**

Air temperature ($T_a$) and relative humidity (RH) were recorded at each site during the transpiration measurements using a TinyTag Plus 2 logger (Gemini Data Loggers, Chichester, UK), with time resolution of 1 min. The logger was placed in a radiation shield on one of the studied trees, on the northern side of its trunk, 2 m above the ground. From $T_a$ and RH, vapour pressure deficit (VPD) was calculated. Thirty-min average values of $T_a$ were used to calculate warming/cooling rates during the daytime and nocturnal measurements. Despite small variation in the timing of daytime measurements, warming rates were calculated between 11 a.m. and 1 p.m. for consistency, as the daytime warming rate is strongly affected by incoming solar radiation. Moreover, diurnal courses of $T_a$ and cooling rates were analysed to find out the timing of the two phases of nocturnal cooling—the intensive, site-specific cooling around sunset (Phase 1, lasting from 1–2 h before sunset until 2–3 h after sunset) and the less intensive, spatially homogeneous cooling later in the night (Phase 2, lasting from 2–3 h after sunset until sunrise). The hourly transpiration measurements (conducted in the period between 1 to 4 h after sunset) were then grouped into Phase 1 and Phase 2. For a detailed explanation of the two phases, see Holmer et al. (2007).

**Table 2** Meteorological conditions on the measurement days: air temperature ($T_a$), vapour pressure deficit (VPD), cloudiness, number of days since last precipitation event and precipitation sum in 20 days prior to measurements. $T_a$ and VPD values represent average conditions during the time of measurements. For days with measurements taken continuously every hour, values are given for the time corresponding best with other measurements

| Species, location | Date | Time of measurements [UTC+1] | | Daytime | | | Night-time | | Days since last precipitation | 20 days precipitation sum |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Daytime | Night-time | $T_a$ [°C] | VPD [kPa] | Cloudiness | $T_a$ [°C] | VPD [kPa] | | |
| Tilia europaea, Stampen | 11.07.2013 | 11:40–13:00 | 23:30–00:20 | 19.9 | 1.30 | Clear sky | 16.2 | 0.71 | 7 | 58 |
| Tilia europaea, Ullevigatan | 20.07.2013 | 10:40–13:30 | 23:40–00:40 | 24.4 | 1.79 | Clear sky | 17.9 | 0.29 | 16 | 13 |
| | 22.08.2013 | 11:15–13:30 | 22:40–00:10 | 21.7 | 1.15 | Low cloudiness | 16.6 | 0.44 | 4 | 27 |
| Tilia europaea, St Sigfridsgatan | 03.09.2013 | 11:00–13:15 | 21:20–22:50 | 20.2 | 0.86 | Low cloudiness | 16.3 | 0.21 | 1 | 20 |
| | 06.09.2013 | 11:10–12:20 | 21:40–22:30 | 22.2 | 1.36 | Clear sky | 17.4 | 0.82 | 4 | 11 |
| Quercus robur | 12.07.2013 | 11:00–13:30 | 21:50–00:00 | 22.7 | 1.63 | Low cloudiness | 17.6 | 0.49 | 8 | 53 |
| | 28.08.2013 | 14:30–15:40 | 21:30–22:30 | 20.6 | 1.05 | Low to moderate cloudiness | 17.0 | 0.63 | 10 | 33 |
| Betula pendula | 09.07.2013 | 10:40–13:00 | 21:30–23:20 | 21.6 | 1.09 | Clear sky | 17.6 | 0.47 | 5 | 67 |
| | 20.08.2013 | 10:50–12:10 | 22:20–23:10 | 18.5 | 0.90 | Low to moderate cloudiness | 16.7 | 0.53 | 2 | 37 |
| Acer platanoides | 20.08.2013 | 12:20–13:10 | 23:20–00:00 | 18.9 | 1.08 | Low to moderate cloudiness | 16.6 | 0.46 | 2 | 37 |
| Aesculus hippocastanum | 23.07.2013 | 10:50–13:00 | 22:00–23:30 | 22.7 | 1.83 | Clear sky | 18.5 | 1.05 | 19 | 6 |
| | 29.07.2013 | 10:40–12:30 | 22:10–23:40 | 23.4 | 1.24 | Low cloudiness | 19.7 | 0.81 | 1 | 37 |
| Fagus sylvatica | 26.07.2012 | 12:30–13:10 | 01:20–02:00 | 23.3 | 1.23 | Clear sky | 16.5 | 0.27 | 4 | 44 |
| Prunus serrulata | 13.07.2013 | 11:00–12:40 | 22:00–23:30 | 19.4 | 0.81 | Low cloudiness | 18.0 | 0.29 | 9 | 48 |
| | 02.09.2013 | 11:40–13:20 | 21:20–22:30 | 17.8 | 1.05 | Clear sky | 13.4 | 0.37 | <1 | 20 |
| Average | | | | 21.2 | 1.22 | | 17.1 | 0.52 | 6 | 35 |

In addition, simultaneous $T_a$ and RH measurements were conducted using another TinyTag Plus 2 logger at a reference urban site with no vegetation. The two loggers were inter-compared before and after measurements and showed a narrow range of $T_a$ readings (0.1 °C at ambient $T_a$ of 20 °C). The reference site was located less than 1 km east from the city centre (Fig. 1), in a street canyon with a sky view factor (SVF, a measure of sky obstruction by buildings or trees, with values ranging from 0 for a clear horizon to 1 for a total obstruction of the sky) of 0.46. The logger was placed in a radiation shield on the northern side of a lamp post, 2.2 m above the ground. Since the nocturnal cooling is strongly affected by SVF, which controls the longwave radiation loss from the surface, data from the reference site was only used for comparison with transpiration measurement conducted at sites characterised by a similar SVF (SVF >0.30, i.e. sites b, d, e, f in Fig. 2; the remaining sites had SVF of 0.20 or less).

Meteorological data (atmospheric pressure, incoming solar radiation and precipitation) were also collected from a weather station located at the rooftop level in the city centre (Fig. 1).

## Results

### The diurnal variation of transpiration

Mean midday stomatal conductance ($g_s$) of sunlit leaves was 126 mmol m$^{-2}$ s$^{-1}$, while $g_s$ of shaded leaves was, on average, half of that value. The highest midday $g_s$ values were observed in case of Q. robur and P. serrulata street trees as well as T. europaea park trees, while the lowest in case of Aesculus hippocastanum and T. europaea street trees. For all studied trees, the leaf transpiration rate ($E_L$) of sunlit leaves was two to six times (on average three times) higher than that of shaded leaves (Fig. 3). Midday $E_L$ ranged from 1.0 mmol m$^{-2}$ s$^{-1}$ (B. pendula) to 3.1 mmol m$^{-2}$ s$^{-1}$ (Q. robur) for leaves

exposed to direct solar radiation and from 0.2 mmol m$^{-2}$ s$^{-1}$ (T. europaea, trees planted along a heavy traffic road) to 1.4 mmol m$^{-2}$ s$^{-1}$ (P. serrulata) for those in shade. Intra-species variations in $E_L$ caused by different weather or growing conditions were also observed, particularly in sunlit leaves. In case of Q. robur and B. pendula, significantly higher $E_L$ of sunlit leaves was observed on the warmer, drier and sunnier of two measurement days, while the $E_L$ rates of shaded leaves were comparable despite varying weather conditions. While the midday $E_L$ values of T. europaea street and park trees were similar (Fig. 3), the analysis of their diurnal variation shows clear intra-species differences (Fig. 4). Among the studied T. europaea trees, average daytime $E_L$ of the sunlit leaves of the park trees was almost twice higher than of the street trees, despite a relatively low $T_a$ and VPD during park measurements (Tab. 2). Daytime $E_L$ of T. europaea growing in a wide grass lawn along a low traffic street (Fig. 4d) was higher than of those growing in a narrow lawn along a heavy traffic road (Fig. 4c), even though the measurements at the former site were conducted at the beginning of September, with less incoming solar radiation and shortly before the trees started to defoliate. Similar differences could not be observed in case of shaded leaves. Interestingly, while the $E_L$ of sunlit leaves of F. sylvatica was relatively low (Fig. 4a), the shaded leaves transpired more intensively than any studied T. europaea trees.

At each of the four sites where measurements were conducted from noon until night-time, hourly $E_L$ increased with increasing VPD and PAR due to stomatal regulation (Fig. 5). The only exception was the T. europaea street trees (Fig. 5d) which showed an opposite behaviour due to an increase of VPD in late afternoon. At all four sites, the relationship of $E_L$ with VPD was more evident in case of shaded than sunlit leaves, as the $E_L$ of sun-exposed leaves was also strongly affected by PAR. The relationships with ambient $T_a$ were generally weaker than with VPD (not shown), since VPD, which



Fig. 3 Average and standard deviation of midday and night-time: (a) stomatal conductance ($g_s$, mmol m$^{-2}$ s$^{-1}$) and (b) leaf transpiration rate ($E_L$, mmol m$^{-2}$ s$^{-1}$). Midday sunlit, midday shaded and night-time values are represented by *white*, *grey* and *black dots*, respectively. In case of T. europaea, three different locations are labelled with letters a–c, according to Figs. 1 and 2
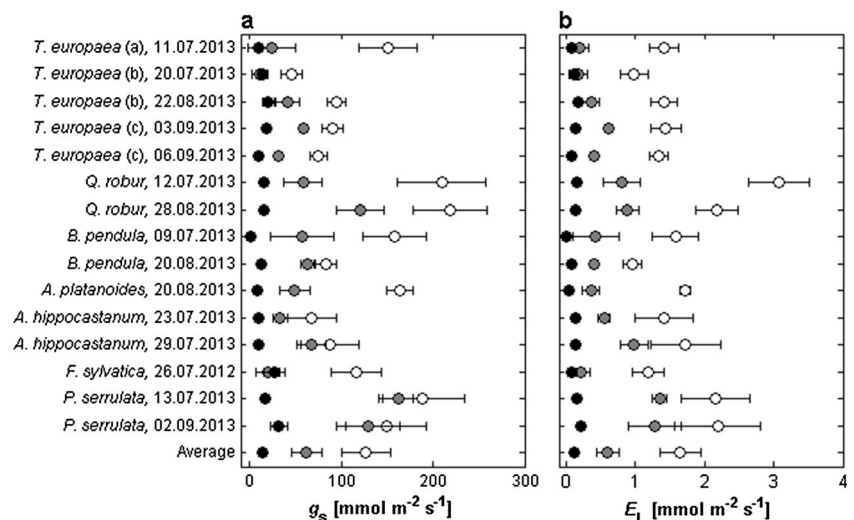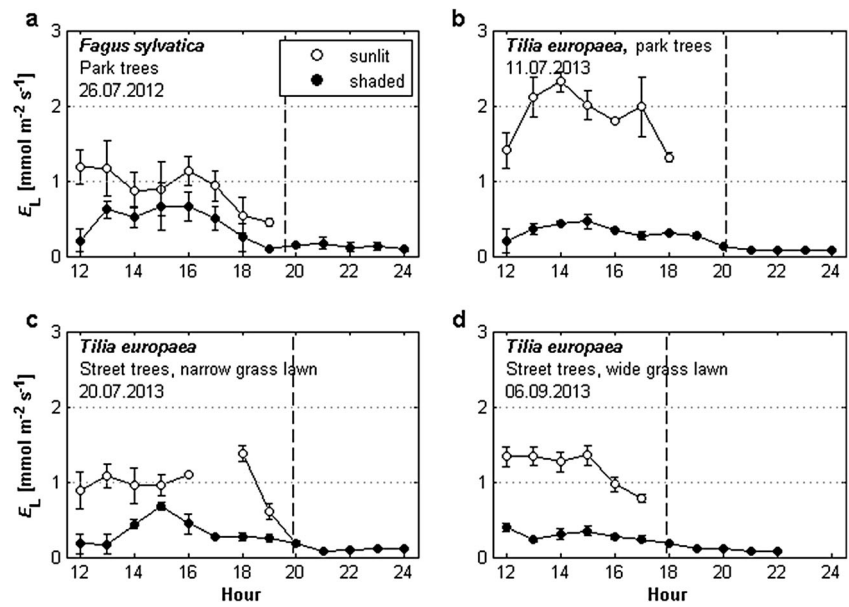
combines the effect of both temperature and humidity of the air, represents the evaporative demand of air better than $T_a$ alone. As a result of decreasing incoming solar radiation and VPD, $E_L$ started to drop around 2–3 h before sunset at each site (Fig. 4). However, transpiration remained active after sunset in all trees studied, indicating an incomplete stomatal closure during night-time. The average night-time $g_s$ amounted to 14 mmol m$^{-2}$ s$^{-1}$, reaching 11 and 23 % of midday $g_s$ of sunlit
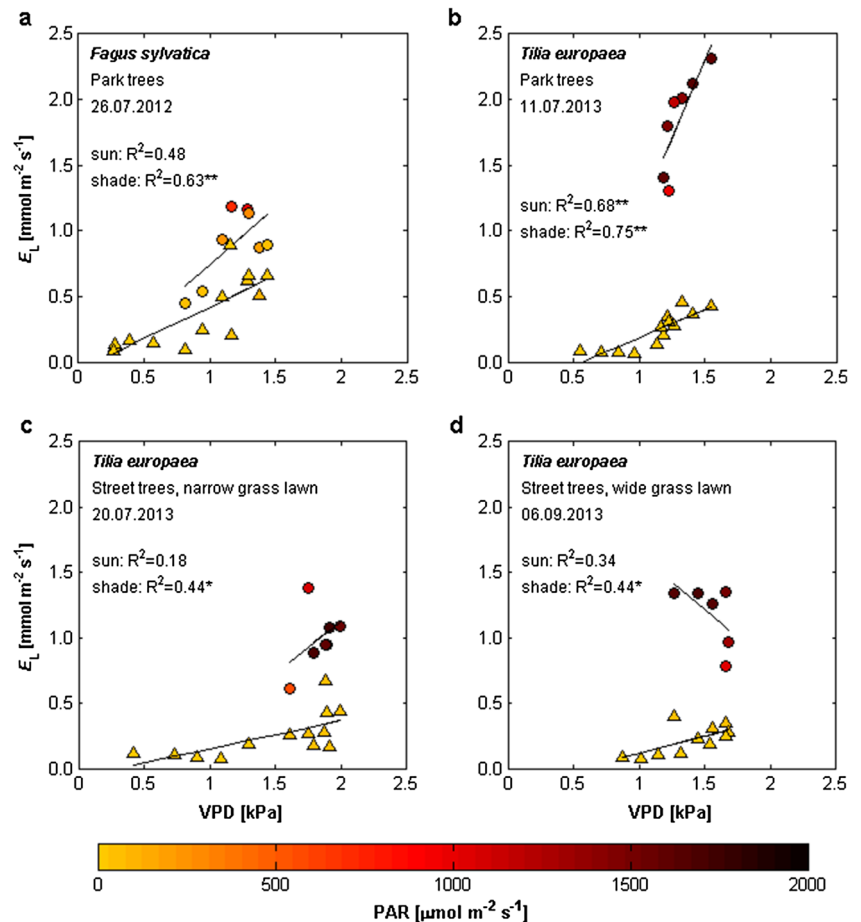
and shaded leaves, respectively (Fig. 3). The night-time $E_L$ values were stable from around sunset until the end of the measurements (1–4 h after sunset) and possibly longer. However, differences in transpiration intensity among various species and measurement days could be observed (Fig. 3). Night-time $E_L$ ranged from 0.005 mmol m$^{-2}$ s$^{-1}$ for *B. pendula* to 0.22 mmol m$^{-2}$ s$^{-1}$ for *P. serrulata*, with a mean value for all species of 0.12 mmol m$^{-2}$ s$^{-1}$. On average across species, night-time $E_L$ reached 7 % of midday $E_L$ of sunlit leaves and 20 % of those in shadow. In general, trees which transpired at a high rate during midday showed a relatively high night-time $E_G$ ($R^2 = 0.35$, $p = 0.02$; not shown).

### Influence of water supply and growing conditions

Except for a relatively wet and cloudy June, when no measurements were conducted, the summer of 2013 was comparatively dry and warm, with periods of over 2 weeks without precipitation. The monthly precipitation in July, August and September amounted to 51, 49 and 56 mm, respectively, which was 30 % lower than the 1961–1990 mean, while the mean monthly $T_a$ was 1.2 °C higher than normal.

Midday $E_L$ and $g_s$ of sunlit leaves were related to the sums of precipitation in periods from 5 to 30 days prior to measurements. The precipitation sum within 20 days prior to measurements (Tab. 2) was found to explain 38 % of variance in $g_s$, indicating a strong stomatal response to soil water availability ($p = 0.015$, Fig. 6a). At the sites where measurements were conducted on 2 days, transpiration rates were in all cases lower after the 20-day period with lower precipitation sum, regardless of VPD, $T_a$ or cloudiness (Table 2, Fig. 3). The only exception was *P. serrulata*, where a relatively high $E_L$, observed after a 20-day period with low precipitation sum, was probably caused by a precipitation event the night before measurements. Relationships with precipitation sums in periods shorter or longer than 20 days were weaker ($R^2 < 0.16$) and statistically insignificant.

Among the seven studied tree species, *Q. robur* and *P. serrulata* had the highest values of $E_L$ of sunlit leaves. At these two sites, trees were planted on 8–18 m wide grass lawns. On the contrary, the lowest $E_L$ values were measured at *T. europaea* growing along a heavy traffic road and *B. pendula*. Both of these sites have poor growing conditions, with the trees surrounded mostly by paved surfaces and planted within a short distance from a road. In general, trees with a higher proportion of permeable surfaces within the vertically projected tree area were found to have a higher $g_s$ than those surrounded by impervious surfaces ($R^2 = 46$ %, $p < 0.01$; Fig. 6b).

In order to roughly estimate the amount of water available for the trees, the sum of precipitation in 20 days prior to measurements was multiplied by the proportion of permeable surfaces within the vertically projected tree crown area (Fig. 6c).
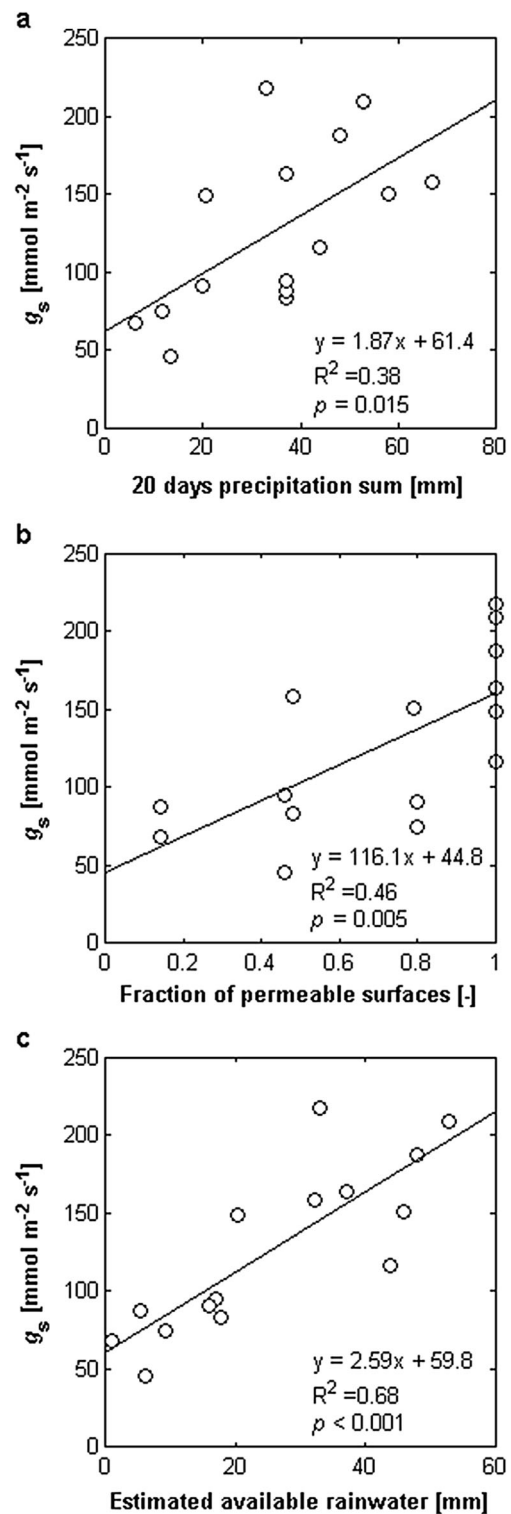
**Fig. 6** Response of daytime stomatal conductance ($g_s$, mmol m$^{-2}$ s$^{-1}$) of sunlit leaves to: **a** precipitation sum in 20 days prior to measurements; **b** fraction of permeable surfaces within the vertically projected tree crown area; **c** their product used as an estimation of available rainwater. Each point represents a different measurement day

Even though such a measure of tree water availability does not take into account differences in soil characteristics, rain

interception or the extent of roots, it explained over two thirds of the variance of $g_s$ of sunlit leaves ($R^2 = 68$ %, $p < 0.001$) across all midday data.

To further analyse the influence of water supply and water conditions on $E_L$, the above described estimated available rainwater was used to divide measurement data into two groups—dry and wet conditions, with the threshold set empirically to 10 mm. The relationships between $g_s$ and $E_L$ in these two groups are shown in Fig. 7. At a certain $g_s$, $E_L$ in dry conditions was higher than in wet. This was presumably due to higher VPD, as the periods of drought were also characterized by high $T_a$ and low humidity. However, the maximum $g_s$ in the dry periods was only half of that in wet conditions and never exceeded 100 mmol $H_2O$ m$^{-2}$ s$^{-1}$, which indicates a response of stomata to water stress. Since the measurements of the seven species were conducted on different days and the growing conditions of trees vary between sites, this study is not ideal for providing direct quantitative information about inter-species differences in $E_L$ or species-specific responses to environmental factors. However, Q. robur and P. serrulata were found to have higher $E_L$ than other studied trees with comparable proportion of permeable surfaces within the projected crown area and exposed to similar weather (Table 2, Fig. 3).

## Latent heat flux and the cooling effect

The estimated latent heat flux per unit area of the vertically projected tree crown ($Q_E$) was on average 206 W m$^{-2}$ (ranging from 72 to 343 W m$^{-2}$ for different study sites) at midday and 24 (ranging from 1 to 38 W m$^{-2}$) at night-time (Table 3). Night-time $Q_E$ ranged from 1 to 24 % of the midday value,
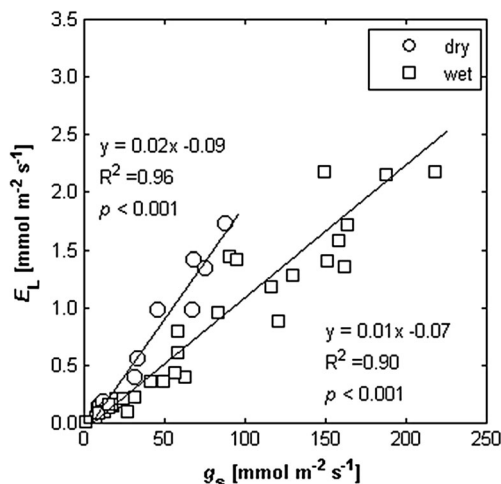


**Fig. 7** Relationship between leaf transpiration rate ($E_L$, mmol m$^{-2}$ s$^{-1}$) and stomatal conductance ($g_s$, mmol m$^{-2}$ s$^{-1}$) in dry ($\leq 10$ mm) and wet (>10 mm) conditions, divided based on the estimation of available rainwater in 20 days prior to measurements. For each measurement day, there are three points representing the mean of midday sunlit, midday shaded and night-time values, respectively

with an average of 13 %. Comparison of daytime $Q_E$ with global solar radiation (Table 3) suggests that within the vertically projected tree area, as little as 9 % (T. europaea, heavy traffic street site) or as much as 64 % (Q. robur) of the incoming shortwave radiation flux (on average 30 %) was converted into latent heat in the transpiration process of the studied trees.

Figure 8 shows the relationship between night-time (a) and midday (b) $E_L$ and the corresponding cooling/warming rate, measured by a $T_a$ logger at each site. In the first phase of cooling, occurring around and shortly after sunset, a higher $E_L$ corresponded with a more intensive cooling ($R^2 = 0.51$, $p = 0.03$). On average, with an increase of $E_L$ by 0.1 mmol m$^{-2}$ s$^{-1}$, cooling rate intensity in Phase 1 increased by 0.25 °C h$^{-1}$. The relationship was also indicated by a slower Phase 1 cooling at the reference site with a similar SVF but no vegetation, and thus no $E_L$. In Phase 2 of nocturnal cooling, starting around 2–3 h after sunset, no significant relationship between $E_L$ and cooling was found, with a similar range of cooling rates at the vegetated sites as at the non-vegetated reference site.

Despite significantly higher daytime than night-time $E_L$, no relationship of tree transpiration and midday warming rate was observed (Fig. 8b). The slightly more intensive midday warming rates at the non-vegetated reference site were presumably caused by a stronger sun exposure of the street canyon than the measurement sites shaded by a tree canopy.

## Discussion

### Daytime transpiration

Midday $E_L$ (1–3 mmol m$^{-2}$ s$^{-1}$) and $g_s$ (45–218 mmol m$^{-2}$ s$^{-1}$) were in similar range to those reported in earlier studies on urban trees. $E_L$ rates of Fraxinus pennsylvanica (Green ash) in Lincoln, Nebraska, ranged from 1.1 and 1.4 mmol m$^{-2}$ s$^{-1}$ for trees planted in small and large pits on a parking lot, respectively, to 1.5 mmol m$^{-2}$ s$^{-1}$ for those surrounded by grass (Cregg 1995). Measurements conducted on street trees in Manchester, UK, showed values of $g_s$ of 50–150 mmol m$^{-2}$ s$^{-1}$ for trees surrounded by asphalt surfaces and much higher values, up to around 400 mmol m$^{-2}$ s$^{-1}$, for those planted in structured soil (Rahman et al. 2011). $g_s$ of park and street trees in Basel, Switzerland, ranged from 125 to 150 mmol m$^{-2}$ s$^{-1}$ for different species except for Tilia tomentosa, Tilia cordata and Platanus acerifolia with values around 200 mmol m$^{-2}$ s$^{-1}$ (Leuzinger et al. 2010). In contrast, we observed relatively low $g_s$ of T. europaea (45–94 mmol m$^{-2}$ s$^{-1}$ for street trees and 151 mmol m$^{-2}$ s$^{-1}$ for park trees) in comparison to other species of this study. Low water use of T. cordata 'Greenspire' street trees in New York was also reported by Whitlow et al. (1992) and Whitlow and Bassuk (1988), particularly in dry

**Table 3** Incoming solar radiation and estimated energy loss due to tree transpiration per unit area of vertically projected tree crown ($Q_E$, W m$^{-2}$)

| Species, location | Date | Incoming solar radiation (midday, W m$^{-2}$) | Energy loss due to tree transpiration, $Q_E$ [W m$^{-2}$] | |
|---|---|---|---|---|
| | | | Midday | Night-time |
| *Tilia europaea*, Stampen | 11.07.2013 | 859 | 92 | 16 |
| *Tilia europaea*, Ullevigatan | 20.07.2013 | 788 | 72 | 13 |
| | 22.08.2013 | 594 | 132 | 20 |
| *Tilia europaea*, St Sigfridsgatan | 03.09.2013 | 572 | 206 | 30 |
| | 06.09.2013 | 609 | 174 | 18 |
| *Quercus robur* | 12.07.2013 | 795 | 343 | 38 |
| | 28.08.2013 | 433 | 390 | 32 |
| *Betula pendula* | 09.07.2013 | 812 | 230 | 1.5 |
| | 20.08.2013 | 528 | 190 | 26 |
| *Acer platanoides* | 20.08.2013 | 613 | 196 | 12 |
| *Aesculus hippocastanum* | 23.07.2013 | 799 | 171 | 32 |
| | 29.07.2013 | 635 | 260 | 31 |
| *Fagus sylvatica* | 26.07.2012 | 809 | 127 | 30 |
| *Prunus serrulata* | 13.07.2013 | 780 | 244 | 25 |
| | 02.09.2013 | 610 | 260 | 35 |
| Average | | 682 | 206±87 | 24±10 |

conditions, and this was attributed to the high sensitivity of transpiration to drought in this species. *Q. robur*, described by Aasamaa et al. (2002) as a drought-tolerant species, had the highest $g_s$ and $E_L$ of all trees measured in this study. High $g_s$ of *Q. robur* saplings (nearly 200 mmol m$^{-2}$ s$^{-1}$) was also reported by Aasamaa and Sõber (2001) and Aasamaa et al. (2002).

The results of hourly measurements on *T. europaea* and *F. sylvatica* trees showed that $E_L$ was strongly influenced by PAR and VPD. These results are in line with earlier studies showing that the daily water use of urban trees in Beijing was governed by VPD, while the hourly $E_L$ depended most significantly on incoming solar radiation (Wang et al. 2011, 2012).

The limited number (1 or 2) of measurement days conducted at each site did not allow for the analysis of response of daily values to varying meteorological conditions. A further study involving more measurement days could provide more detailed information on inter-species variation in transpiration rates in different weather conditions.

Night-time transpiration was active in all studied trees and reached on average 7 and 20 % of daytime $E_L$ of sunlit and shaded leaves, respectively. These values are in good agreement with those reported in other studies, ranging from 5 to 19 % (Snyder et al. 2003; Caird et al. 2007). Based on sap flow measurements on park trees in northern China, Chen
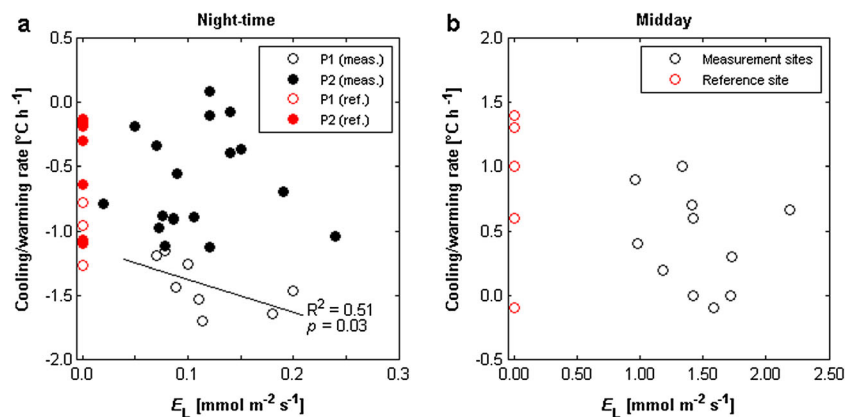


**Fig. 8** Night-time (**a**) and daytime (**b**) leaf transpiration rate ($E_L$, mmol m$^{-2}$ s$^{-1}$) versus cooling/warming rate of the air (°C h$^{-1}$) at the transpiration measurement sites (*black dots*) and a non-vegetated reference site (*red dots*). Night-time data are divided into two phases of nocturnal cooling—Phase 1 (*P1*) lasting until 2–3 h after sunset, and

Phase 2 (*P2*) lasting for the rest of the night. Each point represents a mean hourly value. In case of all-day measurements, more than one hourly value was plotted, depending on the length of measurements after sunset

et al. (2011) estimated the night-time sap flow as 10–19 % of diurnal transpiration of different species. However, values of night-time transpiration in the latter study were presumably lower, since part of the night-time stem sap flux is used for replenishment of water storage within the tree (Phillips et al. 2003).

In general, the highest night-time transpiration was observed in those trees which had the highest water loss during daytime, with daytime and night-time $E_G$ being positively correlated. A similar positive relationship was reported by Snyder et al. (2003) in a hot, dry environment of the western USA.

## The influence of growing conditions of urban trees

Street trees surrounded by asphalt surfaces experience higher evaporative demand than trees growing in natural habitats, due to higher short- and long-wave radiation fluxes as well as typically higher $T_a$ and lower absolute air humidity of the urban environment (Kjelgren and Clark 1992; Kjelgren and Montague 1998; Peters et al. 2010). Such conditions can increase tree water use unless stomatal closure responses compensate for the increase in VPD with little net effect on transpiration. In this study, trees with a higher proportion of permeable surfaces within the vertically projected tree crown area had a higher $g_s$ than those planted in small cut-out pits surrounded by asphalt. Higher transpiration, water loss, net photosynthesis and/or biomass production in trees growing over grass in comparison to those surrounded by impervious surfaces were also observed in urban trees in different climate zones (Close et al. 1996; Celestian and Martin 2005; Mueller and Day 2005; Ferrini and Baietto 2007). An opposite pattern was reported for *Pyrus callayerana* in Illinois, where trees located in a parking lot had a higher water loss than those surrounded by grass, yet a follow-up study on *Fraxinus pennsylvanica* and *Acer platanoides* conducted in Utah showed no difference between water use by trees growing over asphalt and turf (Kjelgren and Montague 1998).

Water stress is commonly described as one of the main reasons behind the short lifespan and poor performance of urban trees (Clark and Kjelgren 1990). None of the trees in this study were irrigated in spite of prolonged periods without precipitation. While irrigation can potentially reduce drought stress of urban trees (Pataki et al. 2011), even regular water additions can be insufficient due to high evaporative demand in urban areas, particularly in hot and dry climates (Whitlow et al. 1992). In such environments, the necessity of conserving water can lead to choosing drought-avoiding species or pruning trees to decrease their total transpiratory leaf area (Chen et al. 2011). Such practices, however, limit the evaporative cooling generated by trees. Instead, increasing the proportion of permeable surfaces around the tree and decreasing the soil compaction can increase the amount of available soil water

without the need of irrigation (Bühler et al. 2006; Nielsen et al. 2007). Trees planted in small pits surrounded by extensive paved surfaces have limited water availability and thus experience water stress more frequently and severely, which can result in lower $g_s$ and transpiration (Fig. 6b).

While the street environment often provides insufficient water resources for urban trees, park trees experience less water stress. They also have lower tree crown temperature compared to street trees surrounded by paved surfaces and thus their cooling effect can be stronger (Leuzinger et al. 2010). As shown in this study, *T. europaea* park trees had a daytime $E_L$ around twice as high as street trees of the same species (Fig. 4). Compared to street and plaza environments, park trees were also found to have increased $g_s$ and transpiration in Lincoln, Nebraska (Cregg 1995) and Seattle, Washington (Kjelgren and Clark 1992), but not in ten common tree species in Basel, Switzerland (Leuzinger et al. 2010).

The product of precipitation sum in 20 days prior to measurements and the proportion of permeable area within the projected crown area was used as a simple measure of tree water availability. Although this crude measure does not account for rainfall interception, soil evaporation, soil compaction and the extent of root system, it explained 68 % of the variance in $g_s$. It is thus a suitable tree water availability index for urban trees that can aid urban structural planning and can serve as a proxy for more difficult and expensive measurements of soil water content and availability.

## Cooling effect

With the estimated mean midday energy loss due to tree transpiration of 206 W m$^{-2}$, on average 30 % of incoming solar radiation was converted into the latent heat flux. Midday to early afternoon evapotranspirative energy loss per unit of vertically projected crown area estimated for street trees in Manchester, UK, by Rahman et al. (2011) was several times higher, amounting to over 1,000 W m$^{-2}$. However, as noted by the authors, the energy loss of Manchester trees was likely overestimated, since the up-scaling from leaf to tree transpiration was based on the assumption that all leaves transpired at the same rate as the measured sunlit leaves. Our data showed that this is an invalid assumption since sunlit leaves transpired at three times as high rates as leaves in the shade.

No significant correlation was found between midday $E_L$ and the warming rate of the air, as the strong vertical and horizontal mixing of the air suppresses the cooling effect of intensive daytime transpiration. This result is in line with a review by Bowler et al. (2010), where a more intensive mean night-time than daytime cooling effect of urban vegetation was reported. It should be noted, however, that despite a limited effect on daytime warming rates or $T_a$, street trees can significantly reduce the heat stress on summer days by

providing shadow (Shashua-Bar et al. 2011; Konarska et al. 2014).

Although the night-time energy loss caused by transpiration was significantly lower than during daytime (on average 24 W m$^{-2}$), it could still contribute to the evening cooling due to higher stability of the air and a shallow depth of the cooled air layer. While during the day the well mixed urban boundary layer can extend vertically up to over 1 km, at night-time its depth is limited to 100–300 m or less (Oke 1987; Eliasson and Holmer 1990). It should be noted that the relationship between cooling rates and $E_L$ could be affected by varying meteorological conditions on different measurement days, with clear, warm weather enhancing both radiative cooling and tree transpiration. However, the contribution of transpiration to the evening cooling was indicated by the relationship between $E_L$ of studied trees and the cooling rate of air in the first part of the night (Phase 1 of nocturnal cooling), as well as a less intensive cooling observed at a non-vegetated reference site with a similar SVF. While transpiration was also observed later in the night, in Phase 2, it was no longer correlated with the cooling rate, possibly due to the development of a capping inversion leading to a spatially uniform cooling (Holmer et al. 2013). These results are in line with studies by Upmanis et al. (1998), Holmer et al. (2007) and Holmer et al. (2013) where a stronger cooling at a vegetated site was only observed in the first part of the night. It should be noted that due to spatially uniform cooling in Phase 2, $T_a$ differences developed around sunset, partly caused by evening tree transpiration, are preserved throughout the night.

## Conclusions

Midday leaf transpiration measured on summer days on mature street and park trees in Gothenburg, Sweden, ranged from less than 1 to over 3 mmol m$^{-2}$ s$^{-1}$ for different species and increased with vapour pressure deficit and photosynthetically active radiation, with on average 30 % of incoming solar radiation being converted into latent heat flux. Midday stomatal conductance had a positive correlation with the fraction of permeable surfaces within the projected tree crown area. Multiplying this ratio by the precipitation sum in 20 days prior to measurements gave a simple, rough estimate of available rainwater, which was found to explain 68 % of variance in stomatal conductance. The observed variations in transpiration rates identified a need for a further study focusing on inter-species variations in transpiration rates under different meteorological and growing conditions.

Night-time transpiration was observed in all studied species and amounted to 7 and 20 % of midday transpiration rate of sunlit and shaded leaves, respectively, with an estimated latent heat flux of 24 W m$^{-2}$. A positive correlation of transpiration rate with the cooling rate of the air as well as a less intensive

cooling at a non-vegetated reference site indicated a contribution of tree transpiration to cooling around and shortly after sunset. No transpirative cooling effect was observed later in the night or during daytime.

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