



Transpiration of urban trees and its impact on daytime and nocturnal cooling in Gothenburg, Sweden

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1. Introduction

Trees can mitigate heat stress in urban areas through shade and evapotranspiration (Mayer et al. 2009; Bowler et al. 2010; Shashua-Bar et al. 2011). 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 environment (Roberts 1977). While transpiration of forest trees has been widely studied, little research has been conducted on the transpirational cooling effect of mature urban trees. Within the urban 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). Knowledge about the transpiration rates of urban trees and how these depend on 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 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 forests and urban parks (Snyder et al. 2003; Fisher et al. 2007; Chen et al. 2011), with an average of 5-15% of the daytime values, as reported in a review by Caird et al. (2007). 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).

The aims of this study are 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.

2. Methods

2.1 Study area

The study was conducted in Gothenburg (57°42'N, 11°58'E), the second largest city in Sweden. The city has a maritime temperate climate, 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, but few street trees in the city. Deciduous trees, which are dominant, usually foliate in late April-early May and defoliate in October.

Seven 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 3 to 6 tree individuals of similar age and dimensions was chosen (Fig. 1). The study sites were characterized by different planting conditions (Tab. 1). 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 lawn width.

2.2 Transpiration measurements

Stomatal conductance (g_s , $\text{mmol m}^{-2} \text{s}^{-1}$) and transpiration rate (E_L , $\text{mmol m}^{-2} \text{s}^{-1}$) per unit one-sided leaf area

were measured using a Li-Cor LI-6400XT Portable Photosynthesis System (LI-COR, Lincoln, USA) with a transparent leaf chamber, under ambient air temperature and humidity, and with a CO₂ mole fraction of 400 $\mu\text{mol mol}^{-1}$.

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. At most sites, measurements were conducted on two days at each site, with one day cloud-free and one 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 one day.

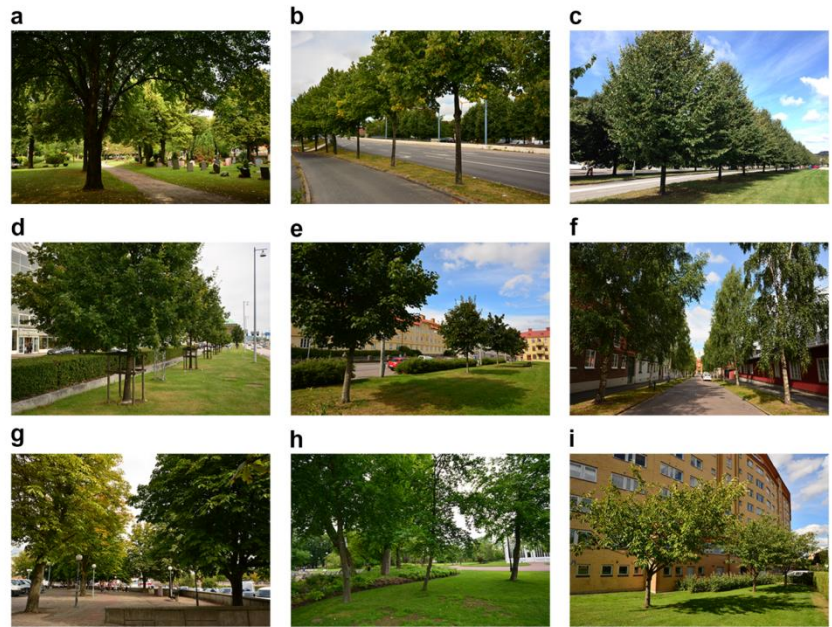


Fig. 1 Photographs of the studied trees

Table 1. Description of study sites. The study sites are labelled according to Fig. 1

| Species | Site | Planting regime | Mean tree height [m] | Fraction of permeable surfaces within the projected tree area | Mean leaf area index, LAI [$\text{m}^2 \text{m}^{-2}$] |
|-------------------------------|------|--|----------------------|---|--|
| <i>Tilia europaea</i> | a | Grass lawn in an urban park | 15.6 | 0.79 | 4.3 |
| | b | Narrow lawn along a heavy traffic road | 8.8 | 0.46 | 2.5 |
| | c | Wide grass lawn along a street | 10.2 | 0.80 | 4.8 |
| <i>Quercus robur</i> | d | Wide grass lawn along a heavy traffic road | 7.3 | 1.00 | 5.4 |
| <i>Betula pendula</i> | e | Pits with grass along a street | 15.1 | 0.48 | 6.5 |
| <i>Acer platanoides</i> | f | Wide grass lawn along a street | 8.2 | 1.00 | 5.5 |
| <i>Aesculus hippocastanum</i> | g | Small pits with bare soil, no grass | 11.9 | 0.14 | 5.0 |
| <i>Fagus sylvatica</i> | h | Grass lawn in an urban park | 10.1 | 1.00 | 7.8 |
| <i>Prunus serrulata</i> | i | Wide grass lawn near a building | 5.8 | 1.00 | 3.6 |

g_s and E_L were measured at low crown level, at the height of around 2 m, on four leaves per tree: two fully sunlit and two shaded during daytime. Since the selected trees were well exposed to sunlight, measurements at this height could be made on fully sunlit leaves. 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.

Leaf area index (one-sided foliage area per unit ground area, LAI, $\text{m}^2 \text{m}^{-2}$) 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). In order to scale up daytime E_L values, the ratio of sunlit (LAI_{sun}) to shaded (LAI_{shade}) leaves was then estimated assuming a random leaf angle distribution, common in broadleaf tree species (Chen et al. 1997). For a detailed description of the LAI measurement and computation, see Konarska et al. (2015).

Transpiration per unit of vertically projected tree crown area (E_G , $\text{mmol m}^{-2} \text{s}^{-1}$) was then calculated by scaling up E_L using the obtained LAI_{sun} and LAI_{shade} values:

$$E_G = E_{L \text{ sun}} \times \text{LAI}_{\text{sun}} + E_{L \text{ shade}} \times \text{LAI}_{\text{shade}} \quad (1)$$

Energy loss per unit ground area (Q_E , W m^{-2}) due to tree transpiration, i.e. latent heat flux within the vertically

projected tree crown area, was calculated by multiplying E_G by the latent heat of vaporisation (λ , J mmol⁻¹) at the measured air temperature (e.g. 44.1 J mmol⁻¹ at 20°C):

$$Q_E = E_G \times \lambda \quad (2)$$

2.3 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 minute. 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. 30 minute 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) 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).

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, in a street canyon with a sky view factor (SVF) of 0.46. 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. 1).

Meteorological data (incoming solar radiation and precipitation) were also collected from a weather station located at the rooftop level in the city centre, within 3 km from any of the measurement sites.

3. Results and discussion

3.1 The diurnal variation of transpiration

Measured 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 other studies on urban trees (Cregg 1995; Rahman et al. 2011)(Fig. 2). *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. The water use of *T. europaea* was relatively low. Whitlow and Bassuk (1988) and Whitlow et al. (1992) attributed the low water use of this species to its high sensitivity to drought. 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.

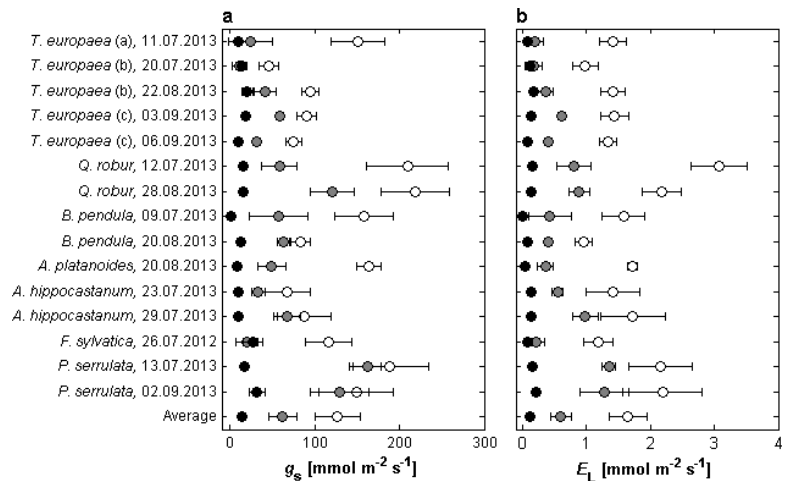


Fig. 2 Average and standard deviation of midday and night-time: a) stomatal conductance (g_s , mmol m⁻² s⁻¹) and b) transpiration rate (E_L , mmol m⁻² s⁻¹). Midday sunlit, midday shaded and night-time values are represented by white, grey and black dots, respectively

As a result of decreasing incoming solar radiation and VPD, E_L started to drop around 2-3 h before sunset at each site (not shown). However, transpiration remained active after sunset in all trees studied, indicating an incomplete stomatal closure during night-time (Fig. 2). 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. On average across species, night-time E_L reached 7% of midday E_L of sunlit leaves and 20% of those in shadow. 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). 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 ($R^2 = 0.35$, $p = 0.02$). A similar positive relationship was reported by Snyder et al. (2003) in a hot, dry environment of the western US.

3.2 Influence of water supply and growing conditions

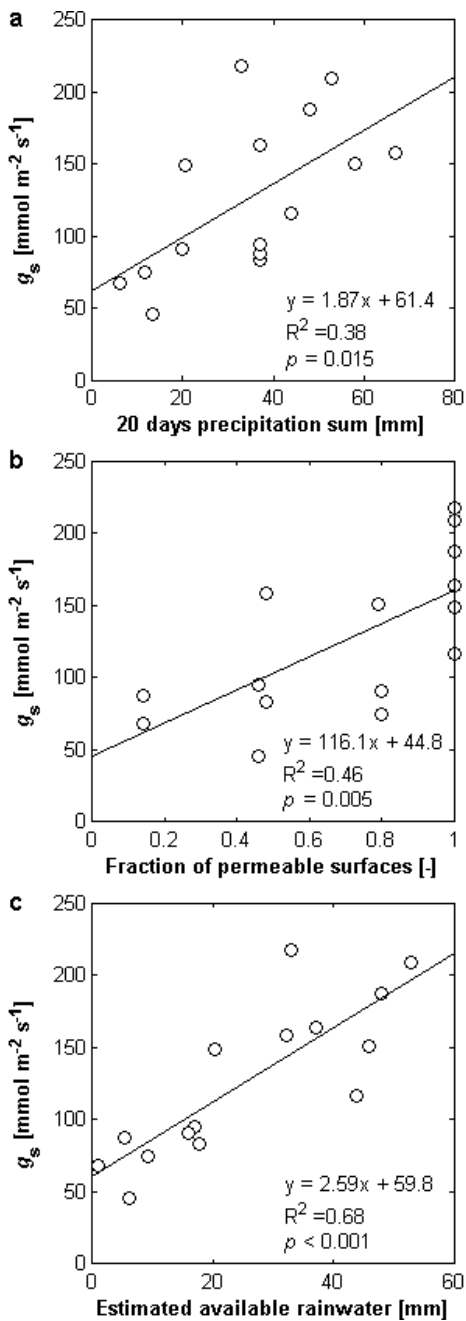


Fig. 3 Midday stomatal conductance (g_s) of sunlit leaves vs: a) 20 days precipitation sum, b) fraction of permeable surfaces within the vertically projected tree area, c) their product used as an estimation of available rainwater. Each point represents a different measurement day

3.3 Latent heat flux and the 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 within the vertically projected tree crown (Tab. 2). 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 1000 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.

Figure 4 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 Phase 1 of nocturnal cooling, 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

Except for a relatively wet and cloudy June, when no measurements were conducted, the summer of 2013 was comparatively dry and warm. The monthly precipitation in July, August and September was 30% lower than the 1961-1990 mean, while the mean monthly T_a was 1.2°C higher than normal (SMHI 2013).

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 was found to explain 38% of variance in g_s , indicating a strong stomatal response to soil water availability ($p < 0.02$, Fig. 3a). At the sites where measurements were conducted on two days, transpiration rates were in all cases lower after the 20 days period with lower precipitation sum, regardless of VPD, T_a or cloudiness. The only exception was *P. serrulata*, where a relatively high E_L , observed after a 20 days 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 ($R^2 = 0.46$, $p < 0.01$; Fig. 3b). 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; Ferrini and Baietto 2007).

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. 3c). Although this crude measure of tree water availability does not account for soil characteristics, rain interception or the extent of roots, it explained 68% of the variance in g_s ($p < 0.001$) across all midday data. It is thus a suitable tree water availability index for urban trees that can serve as a proxy for more difficult and expensive measurements of soil water content and availability.

$\text{mmol m}^{-2} \text{s}^{-1}$, cooling rate intensity in Phase 1 increased by $0.25^\circ\text{C h}^{-1}$ (Fig. 4a). 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 (Tab. 2). 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 also indicated by the 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).

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 (Fig. 4b). 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). The slightly more intensive midday warming rates at the reference site were presumably caused by a stronger sun exposure of the non-vegetated street canyon than the measurement sites shaded by a tree canopy.

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

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

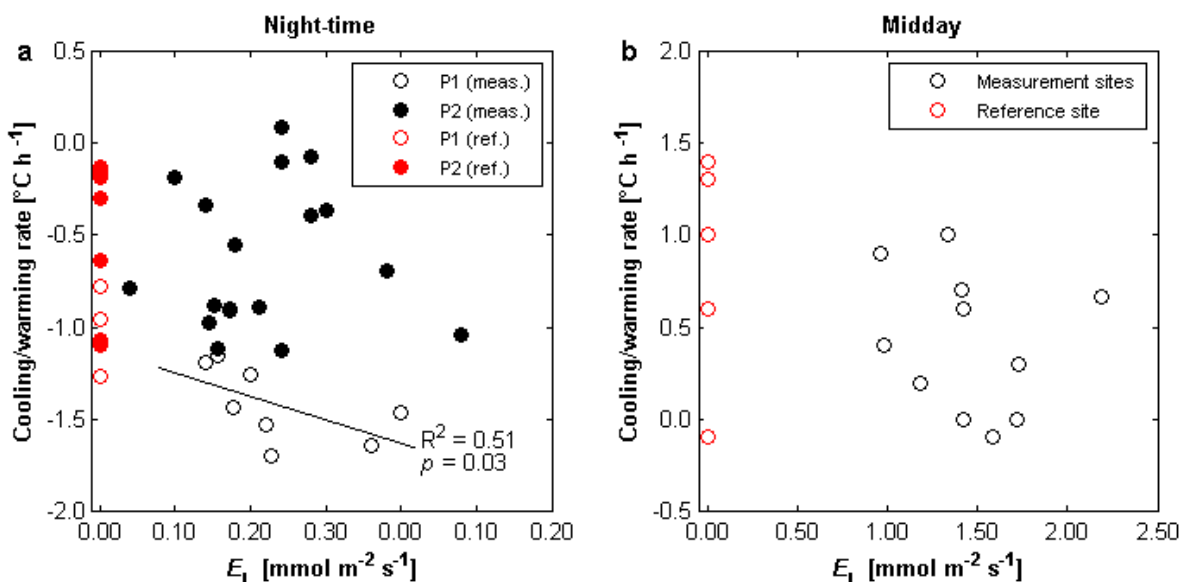


Fig. 4 Night-time (a) and daytime (b) leaf transpiration rate (E_L , $\text{mmol m}^{-2} \text{s}^{-1}$) versus cooling/warming rate of the air ($^\circ\text{C h}^{-1}$) at the transpiration measurement sites (black dots) and a non-vegetated reference site (red dots). Night-time data are divided into 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

4. 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 $\text{mmol m}^{-2} \text{s}^{-1}$ for different species, 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 and 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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