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Quantifying cooling effects of facade greening: Shading, transpiration and insulation

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ABSTRACT

Facade greening is expected to mitigate urban heat stress through shading, transpiration cooling and thermal insulation. This study quantifies cooling effects of facade greenings for the building and the street canyon and distinguishes between transpiration and shading effects. Additionally it discusses insulation effects.

Outdoor experiments were conducted during hot summer periods on three building facades in Berlin, Germany.

We determined transpiration rates (sap flow) and surface temperatures of greened and bare walls as well as of plant leaves (temperature probes) of three climbing plants: *Parthenocissus tricuspidata*, *Hedera helix* and *Fallopia baldschuanica*. Furthermore, air temperature, relative humidity and incoming short-wave radiation were measured.

No cooling effect was detectable for the street canyon. Surface temperatures of the greened exterior walls were up to 15.5 °C lower than those of the bare walls, while it was up to 1.7 °C for the interior wall (measured during night-time). The cooling effects mainly depended on shading, whereas a lower proportion was due to transpiration. Insulation of the direct greenings reduced radiation during night-time. We conclude that greening can be an effective strategy to mitigate indoor heat stress as long as the plants are sufficiently irrigated with up to 2.5 L m^{-2} d^{-1} per wall area.

1. Introduction

Cities often have higher air temperatures than their rural surroundings [1] which is called urban heat island (UHI) effect. Especially at night these differences are high [2]. For instance, measured air temperatures in the densely built-up city centre of Berlin were up to 8 °C higher than the ones of the Grunewald forest in medium low-exchange, nocturnal radiation periods [3].

The UHI phenomenon is mainly caused by the increased absorption of solar radiation by a city surface compared to a natural landscape [4]. It is the result of (i) the city's high surface area due to its vertical structure and (ii) the higher heat storage due to the higher density and higher heat capacity of the built structures compared to natural vegetated surfaces [5]. The higher heat capacity leads to higher long-wave emission of the built structures during the night [6]. Further reasons are increased anthropogenic heat emissions [7] and limited evapotranspiration due to the lack of vegetation [8]. Global climate change is increasing these already higher temperatures in the mid-latitudes cities, which leads to increased heat stress outdoors as well as indoors for the urban population [9].

Heat stress threatens human health and leads to higher mortalities, especially of elderly people (≥65 years) [10,11]. Gabriel and Endlicher [12] could better explain excess mortalities in Berlin by daily minimum air temperatures above 20 °C than by daily maximum air temperatures above 30 °C. This shows the impact of high nocturnal temperatures on sleep disturbances, thus on human well-being and health [13].

Several studies show that urban vegetation reduces the ambient air temperature [e.g. 14]. However, space for horizontal urban vegetation is restricted and its effectiveness is spatially limited for adjacent quarters [15]. Vertical greening seems to be a promising countermeasure to urban heat stress, as it can be applied nearly everywhere in the city, particularly on buildings, the structures in which people mainly suffer from heat stress [13]. Moreover, it is expected to reduce ambient air temperatures because of its high evapotranspiration rate per horizontal base area.

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Facade greening provides cooling towards the greened structures through shadowing, transpiration cooling and thermal insulation [16]. Additionally, it influences the heat distribution in the street canyon by: (i) absorption and conversion of solar radiation into photochemical energy and latent heat which otherwise would be absorbed elsewhere and (ii) cooling the air in the vicinity of the greening, which induces air flow in the canyon.

In the last years, the cooling potential of facade greening has been considered in numerous studies [e.g. 17–19], whereas most of them have concentrated on surface wall temperatures. For instance, Wong et al. [20] found maximum differences in surface wall temperatures between a greened and a bare wall of −11.6 °C. The highest differences so far were measured by Mazzali et al. [21] with differences of up to −20 °C. Most of these studies focus on the shading effect which depends on plant traits such as number of leaf layers, percentage of coverage and leaf solar transmittance [22,23]. Shading reduces energy consumption for air conditioning systems by up to 19% [17]. However, these are results of case studies. So far, no studies are available on water demand and transpiration rates of urban facade greenings, although such information is necessary for a general model on the cooling effects and the sufficient watering of the plants. One opportunity to measure transpiration rates are sap flow measurements, as successfully applied for climbing plants by Leuzinger et al. [24].

Furthermore, there is no sufficient differentiation between shading and transpiration. A first approach was recently started by Cameron et al. [25], who separated these two cooling effects for some plant species including one climbing plant. According to that, *Hedera helix* reduced surface wall temperatures by an average of 7.3 K, for which shading accounted for 60%. However, the plants were potted and standing in front of a wall, not attached to it as usual for facade greenings. Shading and transpiration were differentiated by cutting the stems or sealing the foliage to prevent transpiration, thus not allowing long-term measurements.

In our study, we focus on three typical facade greening species in their typical settings inside the city, attached to the walls: *Parthenocissus tricuspidata*, *Hedera helix* and *Fallopia baldschuanica*. We (i) quantify the cooling effects of facade greening for the building and the ambient urban air and (ii) distinguish between transpiration and shading effects. Additionally we discuss insulation effects. Finally, we (iii) quantify the water demands of the investigated facade greening species as a prerequisite for an effective cooling.

2. Materials and methods

2.1. Plant species

Three different climbing plants were investigated: *Parthenocissus tricuspidata*, *Hedera helix* and *Fallopia baldschuanica*.

P. tricuspidata is originally distributed in Asia and North America. *H. helix* is an evergreen climbing plant with its natural habitat in European woodlands. Both, *P. tricuspidata* and *H. helix*, are self-clinging climbers which climb directly on the building surface with their adhesive pads and their adventitious roots, respectively. They are well-examined [e.g. 26–28] and also widely used as facade greening plants in mid-latitude cities.

F. baldschuanica is a deciduous rambling plant originating from Asia that needs climbing aids for its upward growth. It is a very fast-growing and relatively undemanding climbing plant.

2.2. Study sites

In order to study the cooling effects of facade greenings, measurement campaigns were carried out on three building facades at the campus of the Technische Universitaet Berlin, in the city centre of Berlin, Germany (lat. 52°51′ N, long. 13°32′ E). In each case, the investigated facades were greened on one half, while the other half was bare.

The following facades were investigated:

(a) Site A (Fig. 1a): a south south-west exposed facade of a building greened with *P. tricuspidata* which clung directly on the wall ("direct facade greening" according to Hunter et al. [28]). The plants rooted in a raised bed filled with humic sand (unsealed area about 6 m^2) and were supplied with water in irregular intervals. The measurement campaign on this building facade was carried out from 19th July to 16th August 2013.

(b) Site B (Fig. 1b): an east exposed facade with a dark coloured wall surface which was greened with *H. helix* (adult type). As described for the first site, the plants were attaching themselves on the building facade without technical climbing support. During the experiment, the plants were additionally supplied with water. The measurement campaign lasted from 1st August to 6th August 2014.

(c) Site C (Fig. 1c): a west exposed facade (a 12 m high gable wall of a large hall, with only one big room inside, heated in winter but not air conditioned in summer) greened with *F. baldschuanica*. The plants had additional climbing support structures 0.3 m in front of the wall, leaving an air cavity of about 0.2 m ("double-skin green facade" according to Hunter et al. [28]). They were planted in containers with humic sand and supplied with nutrient solution from a constant standing water table in 0.45 m depth. Thus, they were perfectly irrigated except of a drought experiment taking place from 16th to 20th September 2014. In that period, no irrigation took place, only the water stored in the substrate was left for the plants. Measurements on this facade were carried out since August 2013.

To calculate the wall leaf area index (WLAI, mean leaf area corresponding covered wall area) of the whole facade greenings, we harvested the leaves of at least 2 m^2 vertical area in different heights for every facade greening at the end of the measurement campaign. WLAI of the investigated facades was 1.9 for *P. tricuspidata*, 3.0 for *H. helix* and 3.0 for *F. baldschuanica*. We also determined the area of the leaves on the stems used for sap flow measurements (see below) to calculate the transpiration rate based on leaf area (LA) and wall area (WA).

2.3. Meteorological measurements

At each site, we measured the surface temperatures of the bare exterior wall ($n = 3$), the exterior wall behind the greening ($n = 3$) and of the plant leaves ($n = 5$) (SKTS 200 U^{-1} 10k Thermistor, Umweltanalytische Produkte, Germany) (Fig. 1a–c). At site C, additionally the surface temperatures of the interior building wall were measured for the vegetated and bare segments ($n = 3$ each), which both belonged to the same room. No further indoor climate parameters were measured.

For building facade A and B, meteorological measuring stations were installed 0.4 m in front of the bare and the greened facade at approximately 2.8 m above the ground. Air temperature, relative humidity (RFT-325, Driesen + Kern, Germany; HC2-S3, Rotronic Messgeräte, Germany) and incoming short-wave radiation reaching the facade (SP-110, Apogee Instruments, Inc., USA; LP02-05, Hukseflux Thermal Sensors B.V., the Netherlands) were measured in 5-min intervals. Incoming radiation is given in W m^{-2}, while its cumulative sum for the whole day is given in J m^{-2}. Due to the distance between the greened and the bare station at facade A (Fig. 1a), the diurnal courses of the incoming short-wave radiation at both stations were slightly time-shifted. On a daily base however, the

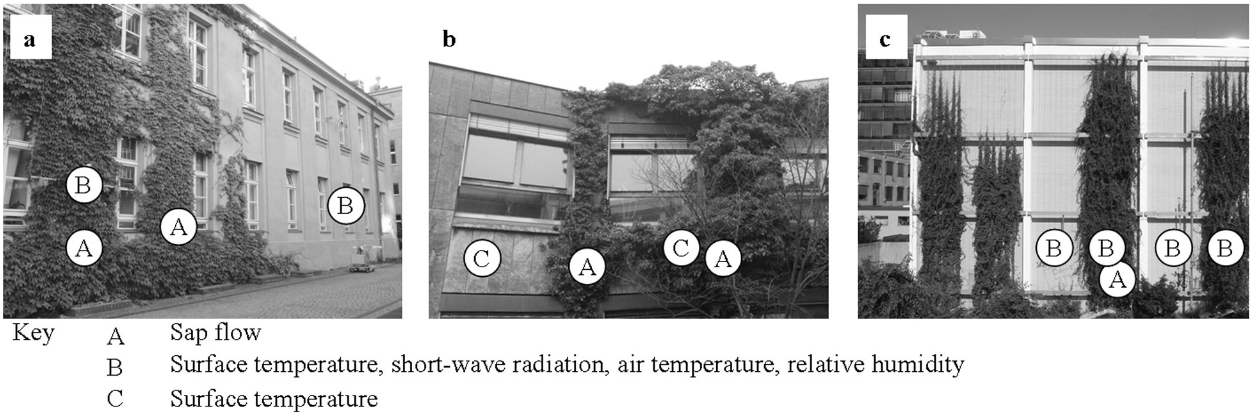

Fig. 1. Three investigated building facades and the experimental designs: (a) south south-west exposed facade greened with *Parthenocissus tricuspidata* (b) east exposed facade greened with *Hedera helix* and (c) west exposed facade greened with *Fallopia baldschuanica*.

differences between both positions were less than 0.2% of the total radiation and consequently negligible.

The accuracy of the temperature probes was 0.1 °C while the uncertainty of the radiation measurements was 0.15×10^{-6} V W^{-2} m^{-2}.

2.4. Quantifying shading

In order to calculate the cooling effect through shading, another short-wave radiation sensor was installed behind the greening at site A and C. Shading effect S (W m^{-2}) was calculated by the following equation:

$$S = K{\downarrow}_f - K{\downarrow}_b \tag{1}$$

where $K{\downarrow}_f$ (W m^{-2}) is the incoming short-wave radiation in front, and $K{\downarrow}_b$ (W m^{-2}) the incoming short-wave radiation behind the greenery.

2.5. Quantifying transpiration

Transpiration rates of the climbing plants were determined by sap flow gauges (Sap flow module EMS 62, EMS Brno, Czech Republic) based on the stem heat balance method, with external heating and internal temperature sensing, described in detail by Lindroth et al. [29]. For every facade greening, several main stems were instrumented, wrapped with insulation foam and shielded against direct solar radiation and precipitation. Sap flow Q_s, measured in a 1-min resolution, is expressed on a volume base, assuming a water density of 1 g cm^{-3}. It was calculated by the following equation [29]:

$$Q_s = \frac{P}{\Delta T c_w} - Q_{fic} \tag{2}$$

where P (J s^{-1}) is the recorded power input to the heater, ΔT (K) is the adjusted constant temperature difference between the two needles, c_w (J kg^{-1} K^{-1}) the specific heat of water and Q_{fic} (L s^{-1}) a fictitious flux of water, caused by the heat loss from the sensor. Q_{fic} was determined as the lowest measured sap flow during night-time, assuming that actually no transpiration occurred in these periods [29]. In order to estimate the cooling effect through transpiration as energy equivalent (W m^{-2}), we assumed an evaporation heat of 2450 J g^{-1} water (20 °C).

All measured data were aggregated to a half hourly resolution afterwards.

2.6. Quantifying the emitted energy during night-time

We assume that the stored heat from the wall is emitted completely into the street canyon during the night. That is because of the higher temperature gradient in the street-canyon direction compared to the interior building direction in the summer. The emitted energy $Q{\uparrow}$ (W m^{-2}) from the walls was calculated as follows:

$$Q{\uparrow}_{green} = \Delta T_{green} * c_p * m \tag{3}$$

$$Q{\uparrow}_{bare} = \Delta T_{bare} * c_p * m \tag{4}$$

where the subscripts $_{green}$ and $_{bare}$ indicate the greened and bare walls; ΔT (K) is the difference of the exterior wall surface temperatures between calendrical dusk and dawn, c_p (J kg^{-1} K^{-1}) the specific heat capacity of the wall, set to 836 J kg^{-1} K^{-1}; m (kg m^{-2}) is the mass of the wall per m^2 WA. It was calculated to be 295 kg m^{-2}, based on the following information about the wall at site C: it was 0.29 m thick in total, consisting of a 0.24 m thick masonry (specific density assumed 1120 kg m^{-3}) plus 0.01 m tiles (1900 kg m^{-3}) and 0.04 m wood wool insulation (155 kg m^{-3}). In order to compare the results, we assumed that the walls at all sites are identical.

3. Results and discussion

3.1. Diurnal variations in irradiation and transpiration

Fig. 2a and b display the meteorological conditions and the sap flow, exemplarily shown for *P. tricuspidata* on a hot (2nd August) and on a cold summer day (14th August).

On the hot day, the sky was practically cloud-free. Air temperature and relative humidity varied from 21.2 to 37.4 °C and from 46.4 to 68.1%, respectively. In front of the greened wall, we measured a cumulative incoming short-wave radiation of 13,761,000 J m^{-2}. The diurnal course of $K{\downarrow}_f$ is characteristic for a vertical structure like a facade. Right after sunrise, $K{\downarrow}_f$ increased slowly due to indirect radiation. When the sunlight reached the facade directly at about 10:00, $K{\downarrow}_f$ increased strongly. The course also demonstrates the typical situation of facades in an urban setting, namely the impact of surrounding buildings. They were shading the facades (reduced sky view factor), leading to reduced total insolation and very sharp increases and decreases of $K{\downarrow}_f$ when the building was no longer shaded or was shaded again. However, reflections from buildings can also lead to increased irradiation compared to non-urban situations. With sufficient temporal resolution, several reflections from buildings opposite to the wall are visible (Fig. 3). This reflected radiation accounted for up to 105 W m^{-2} and caused detectable sap flows.

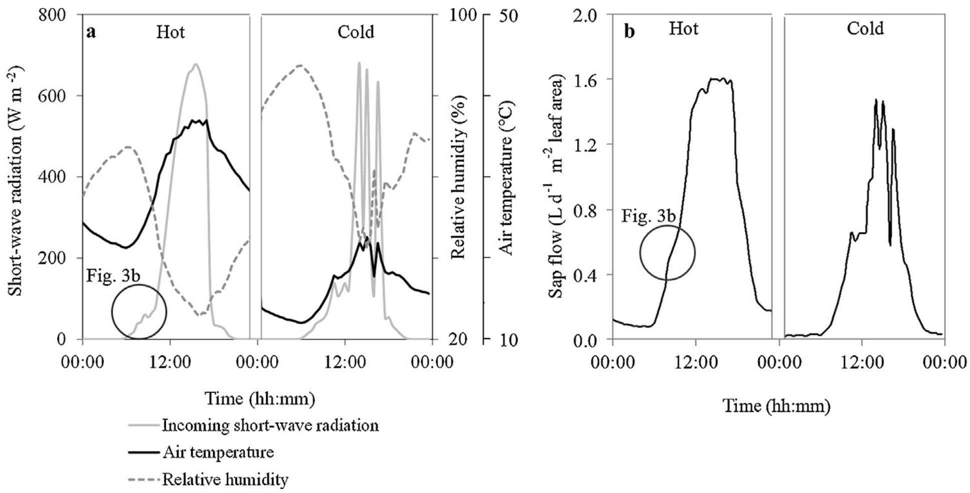

Fig. 2. (a) Meteorological conditions in front of the greened wall on a hot (2nd August 2013) compared to a cold summer day (14th August 2013). (b) Mean diurnal sap flow (*Parthenocissus tricuspidata*) on these two days. All results for a south south-west oriented facade in Berlin, Germany.

On the cold summer day, air temperature and relative humidity varied from 12.0 to 24.4 °C and from 37.7 to 88.0%, respectively. Cumulative incoming short-wave radiation was reduced by about 37% compared to the hot day (8,634,000 J m^{-2}).

Sap flow rates were almost similar for all investigated plant stems at each facade (data not shown). Thus, mean values are discussed in the following. The diurnal course of the sap flow was strongly influenced by incoming short-wave radiation, air temperature and relative humidity, with the first being the most influencing factor. With 0.1 and 0.03 L d^{-1} m^{-2} (LA) on the hot and on the cold day, sap flow was low during the night and increased with the first detectable incoming short-wave radiation in the morning (Fig. 2b). Moreover, similar to short-wave radiation, it rose sharply from the point when the sun shone directly on the facade. On the hot day at noon, the sap flow curve is flattened and oscillated. The potential transpiration rate of the plant was probably reached, which may have been caused by three different phenomena: very high radiation can lead to narrowing to up to closing of the stomata for some plant species [30]. A second reason could be that despite irrigation, there was not enough water available fulfilling the highest water demands. A corresponding wilting of the leaves was not observed. Therefore, it is more probably that the transpiration demand exceeded the maximum water conductivity of the plant system.

3.2. Cooling effects of facade greening

When comparing ambient air temperatures in front of the greenings with those in front of the bare walls, no differences were found over the daily course for all investigated sites (Fig. 4a and b). The detected differences were 0.03 (Site A) and 0.2 °C (Site C) which is in the range or at least near to the measuring uncertainty. At site A, at noon, the air temperature in front of the greened wall was slightly higher than in front of the bare wall, whilst in the evening it was reverse. This is due to the fact, that the greened wall receives the sunlight earlier than the bare wall, as described above. Mixing air, due to large-scale weather pattern induced winds or micro-scale facade-greening induced air parcels in front of the greening,

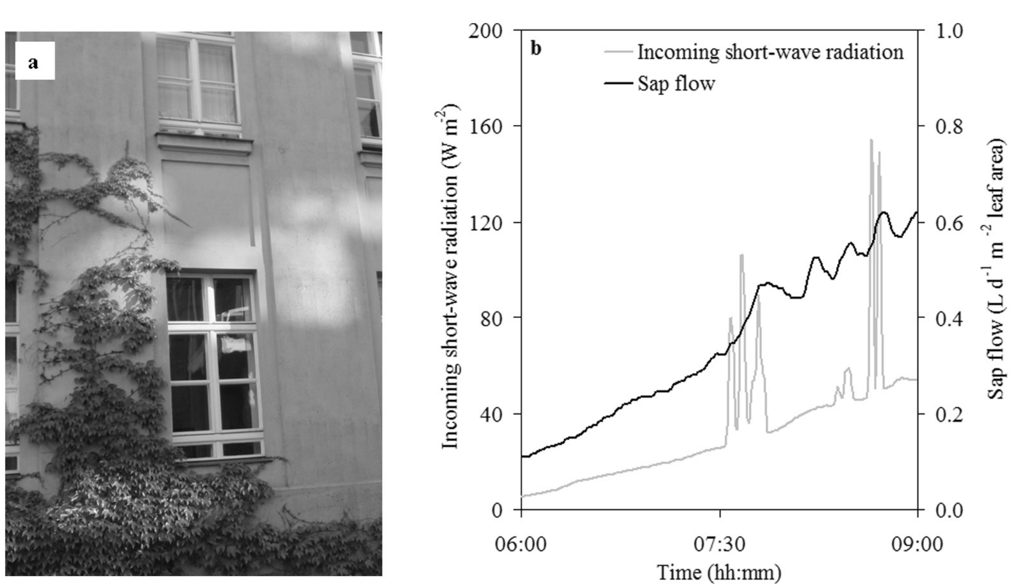

Fig. 3. (a) Window reflections of a facing building. (b) Indirect incoming short-wave radiation with peaks due to window reflections of a facing building and sap flow reactions of *Parthenocissus tricuspidata* on the 2nd August 2013.

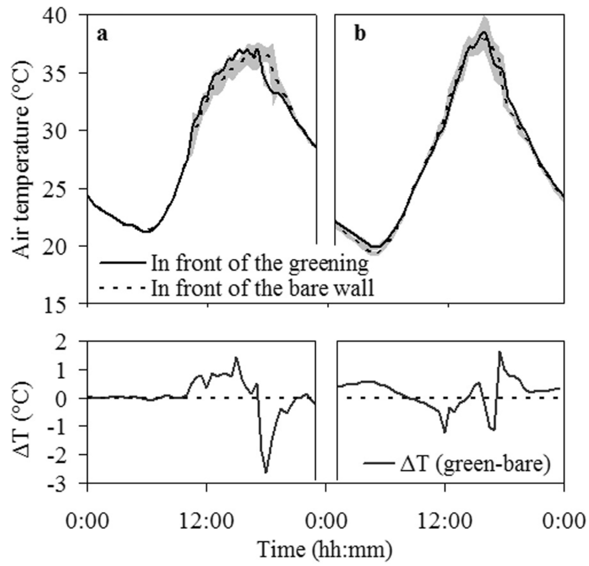

Fig. 4. Mean air temperatures in front of the greenings and the bare building walls (at the top) as well as temperature differences between both of them (at the bottom) on hot summer days, (a) south south-west exposed facade greened with *Parthenocissus tricuspidata* (2nd August 2013) and (b) west exposed facade greened with *Fallopia baldschuanica* (19th July 2014). The grey area indicates the standard deviation of the given mean values.

is probably the main reason for no clear differences in ambient air temperature. Facade-greening induced mixing air can be caused by density differences of air parcels with different temperatures and humidities as hypothesised by Krawina and Loidl [31].

While we could not measure a cooling effect for the ambient air in the street canyon, the effect for the building was clearly detectable (Fig. 5a–c). Mean surface temperature of the greening with *P. tricuspidata* (Site A) was reduced by 0.1 to 11.3 °C (on average 3.3 K) compared to the surface of the bare exterior wall for a hot summer day (28th July 2013). Similar results were found for the greening with *H. helix* (Site B) (0.0–12.3; avg. 3.7), while it was weaker pronounced at the greening with *F. baldschuanica* (Site C) (−0.8 to 6.6; avg. 2.4).

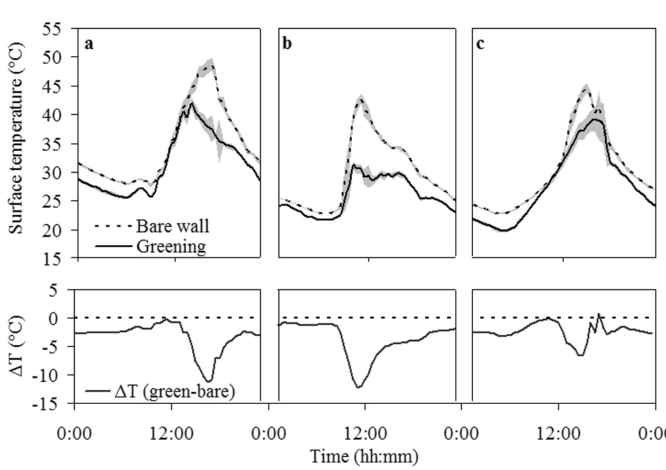

Fig. 5. Mean surface temperatures of the greenings (leaves) and the bare exterior building walls on the three investigated facades (at the top) as well as temperature differences between both of them (at the bottom) on hot summer days, (a) south south-west exposed facade greened with *Parthenocissus tricuspidata* (28th July 2013), (b) east exposed facade greened with *Hedera helix* (3rd August 2014) and (c) west exposed facade greened with *Fallopia baldschuanica* (19th July 2014). The grey area indicates the standard deviation of the given mean values.

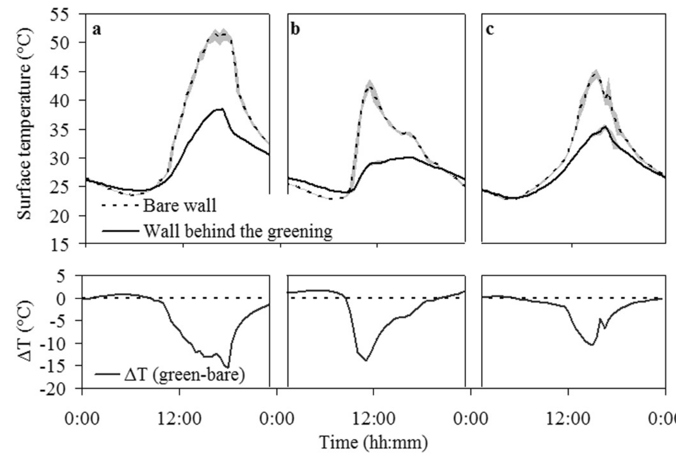

Fig. 6. Mean surface temperatures of the greened and bare exterior building walls on the three investigated facades (at the top) as well as temperature differences between both of them (at the bottom) on hot summer days, (a) south south-west exposed facade greened with *Parthenocissus tricuspidata* (2nd August 2013), (b) east exposed facade greened with *Hedera helix* (3rd August 2014) and (c) west exposed facade greened with *Fallopia baldschuanica* (19th July 2014). The grey area indicates the standard deviation of the given mean values.

Greening also decreased the surface temperatures of the exterior side of the building wall at all three sites (Fig. 6a–c). The highest temperature reduction was reached for site A, the south south-west exposed facade: the bare wall was heated up to 51.5 °C on a hot summer day at 16:30 (2nd August), while in contrast, it was only 38.3 °C at 16:00 on the wall surface behind the greening. The maximum difference between the greened and bare wall occurred in the late afternoon at 18:00 with −15.5 °C. For the other building facades, the maximum temperature difference reached up to −13.9 °C (Site B) and −10.5 °C (Site C). On the daily average, the greened walls were cooler, with a difference of −4.4 °C (Site A), −2.2 °C (Site B) and −2.2 °C (Site C).

Interestingly, Susorova et al. [18] found average and maximum differences of only −1.1 and −7.9 °C for *P. tricuspidata* at a south exposed facade in Chicago, USA (lat. 41°50′ N). Ambient air temperatures ranged from 20.7 to 38.8 °C, which were very much in the same range as in our experiment. As in both experiments the maximum vegetated wall temperatures were similar (37.4 in Berlin and 38.3 °C in Chicago), the lower differences measured in Chicago might be due to a higher albedo of the building envelope. This envelope was assembled from glass, steel and light coloured tiles and led to a maximum surface temperature of the bare wall of only 41.5 °C, compared to the 51.5 °C in Berlin. The same phenomenon could be observed in Berlin at site C, where we have a similar envelope to Chicago and where we detected the lowest maximum difference. We conclude that the cooling effect of facade greening is even more effective for surface wall temperature reduction than the best architectonical practice for the bare wall case, a light wall with glossy surfaces and a high solar reflectance.

Due to insulation of the vegetation cover, the bare walls cooled down much faster than the greened walls and were actually cooler during the night (Fig. 6a–c). This insulation effect increases with increasing leave area density and thickness of the greenery for direct facade greenings. While the difference between the greened and the bare wall was up to 0.8 °C at site A, where the plants had a WLAI of 1.9, it was up to 1.6 °C on site B, where WLAI was 3.0. The difference for the well ventilated double-skin facade at site C was only up to 0.3 K, although having a comparable high WLAI of 3.0.

The insulation effect might be a disadvantage of facade greenings concerning the cooling effect for the individual building, especially because people mainly suffer from heat stress at night. However, for cooling the quarter and the street canyon, the

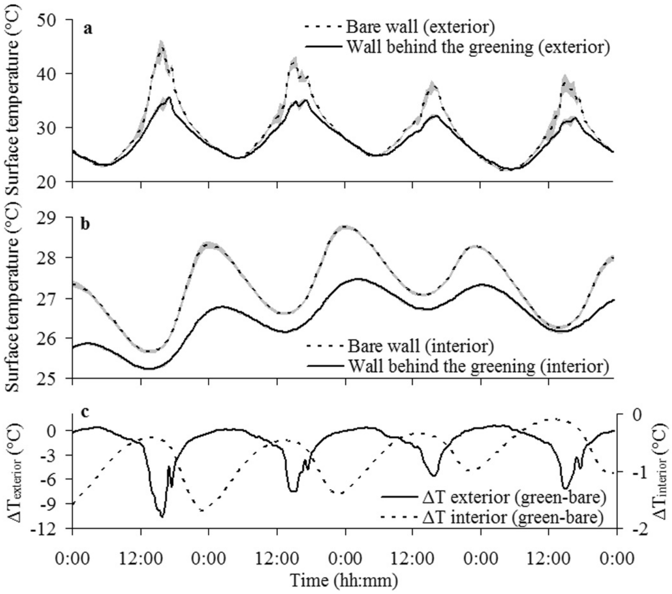

Fig. 7. Mean surface temperatures of the greened and bare (a) exterior building wall, (b) interior building wall as well as (c) temperature differences between the greened and the bare walls in a hot summer period (19th to 22nd July 2014). All results are for a west exposed facade greened with *Fallopia baldschuanica*. The grey area indicates the standard deviation of the given mean values.

insulation effect of direct facade greening is positive. At site A (2nd August 2013 21:40 to 3rd August 2013 04:50) and B (3rd August 2014 21:40 to 4th August 2014 04:50), the bare walls emitted 64.5 and 43.9 W m^{-2} while the greened walls emitted 36.5 and 34.1 W m^{-2}, respectively. The bare wall at site C heated the canyon with 50.4 W m^{-2} during night-time (19th July, 22:05 to 20th July, 04:25), while the greened surface emitted only 41.3 W m^{-2} at site C.

These findings demonstrate the high impact of the design of facade greenery on the cooling effectiveness for the building. While the air could circulate behind the plants at site C, the greeneries at sites A and B stopped air circulation or at least reduced air velocities in front of the wall [32]. The design at site C was favourable to reduce the insulation effect at night, demonstrated by the highest nocturnal emission of energy of the three greened facades.

Beside the air cavity between wall and greening, it had a free lateral access to moving air as not the whole wall was greened but only some strips (Fig. 1c). In conclusion, for the building cooling, it would be most effective if the greenery could be oriented in parallel during the day and perpendicular to the wall during the night (that aspect can discussed differently for winter times). However, the insulation effect of facade greening on the overall building cooling effect can only be discussed based on interior wall surface temperatures.

As expected, the cooling effect through the greenery was also detectable on the interior building wall, shown for the west exposed facade at site C greened with *F. baldschuanica* (Fig. 7a–c). The interior wall of the greened facade heated up to max 27.5 K, whereas it was max 28.8 °C for the bare wall. The greened facade was always cooler (average $\Delta T = -0.9$ K) with a maximum difference of −1.7 °C. Altogether, the reduction potential of the greening on interior wall temperature is not extraordinary great, but Buchin et al. [11] revealed that already a mean air-temperature reduction of 0.8 °C can reduce the numbers of heat-related deaths.

It is remarkable that the peaks of the interior surface temperature occurred around midnight and were timely shifted to the peaks of the exterior surface temperature. This time lag amounts to 6–8 h for the 0.29 m thick wall.

3.3. Transpiration and shading

Fig. 8a and b show the total cooling effect as well as the differentiation between shading and transpiration for *P. tricuspidata* and *F. baldschuanica* on clear summer days. During the night, cooling only depended on transpiration, which was relatively low for *P. tricuspidata*, with values between −1.5 and −5.5 W m^{-2}, and a bit higher for the well-irrigated *F. baldschuanica*, with values between −9.7 and −60.6 W m^{-2}. With the first detectable solar radiation, shading became effective.

The total cooling effect of *P. tricuspidata*, was highest from 12:00 to 16:00 with a peak of −585.6 W m^{-2} at 14:00 for a hot summer day (2nd August 2013) with high solar radiation. In this period, shading accounts for 87% of the total cooling. For the whole day, shading accounts for only 81.5% of the total cooling. We found the same proportions for a cold summer day with less radiation during daytime (14th of August 2013, data not shown). The greening of *P. tricuspidata* retained or reflected 75.3% of the incoming short-wave radiation (transmissivity = 0.25). Ip et al. [22] found leaf solar transmissivities for *P. tricuspidata* between 0.12 and 0.45, depending on the number of leaf layers. Furthermore, the shading effect changed throughout the year due to leaf-growing and leaf-shedding with maximum shading performance in August and September [22].

For *F. baldschuanica*, at the 3rd September 2014 the peak cooling of −755.8 W m^{-2} occurred at 15:30, thus later as at site A due to the west exposition. It depended on shading to 79.4% and on transpiration to 21.6%. For the whole day, transpiration had a higher contribution of 39.9%. For a 13 days measuring period (3rd to 15th September 2014) with nice late summer weather conditions (average air temperature = 19.2 °C, average daily cumulative incoming short-wave radiation = 5,149,086 J m^{-2}), transpiration contributed to almost the same extent as shading (transpiration = 47.5%). For a cloudy day (12th September 2014), the proportion of transpiration was even 73% on a daily base (Fig. 8c). However, the total cooling effect for this day was relatively low with a peak of only −79.5 W m^{-2}. During the dehydration experiment, the contribution of transpiration on the total cooling effect decreased to only 6.1% due to water stress (Fig. 8d). For *F. baldschuanica* the transmissivity was only 0.09 as measured in September 2014.

Whether the differences in contributions of shading and transpiration for *P. tricuspidata* and *F. baldschuanica* on the total cooling effect are only plant specific or also due to the irrigation status or the meteorological conditions could not be completely assessed in this study. However, we could show that these factors influence the proportioning of the total cooling effect to a large extent.

3.4. Transpiration rates and water demand

The daily transpiration rates per unit LA were similar for the three investigated climber species with an average of 0.5 L d^{-1} m^{-2} (Table 1). However, in preliminary indoor studies, *F. baldschuanica* was the species with the highest daily transpiration rate of 2.7 L d^{-1} m^{-2} (LA) [33]. The lower rates in this outdoor experiment can be explained by the measurements done in September and not in August like for the other plant species (due to technical reasons). Consequently, incoming global radiation and air temperatures were lower during those measurements.

The daily transpiration rates per unit WA were lowest for *P. tricuspidata* due to the lower WLAI. On the 2nd August (hot day), with 1.3 L d^{-1} m^{-2} (WA) we measured the highest daily transpiration rate for this species. The lowest daily transpiration rate was measured on the 14th August (coldest day) with only 0.7 L d^{-1} m^{-2} per unit WA. This corresponds to an average energy conversion between 19.9 and 35.4 W m^{-2} (WA). Estimated exemplary for the whole greened facade of 36 m^{2} at site A, a water amount of 25.2 to 45.0 L d^{-1} is needed in summer. However, for typical urban sites

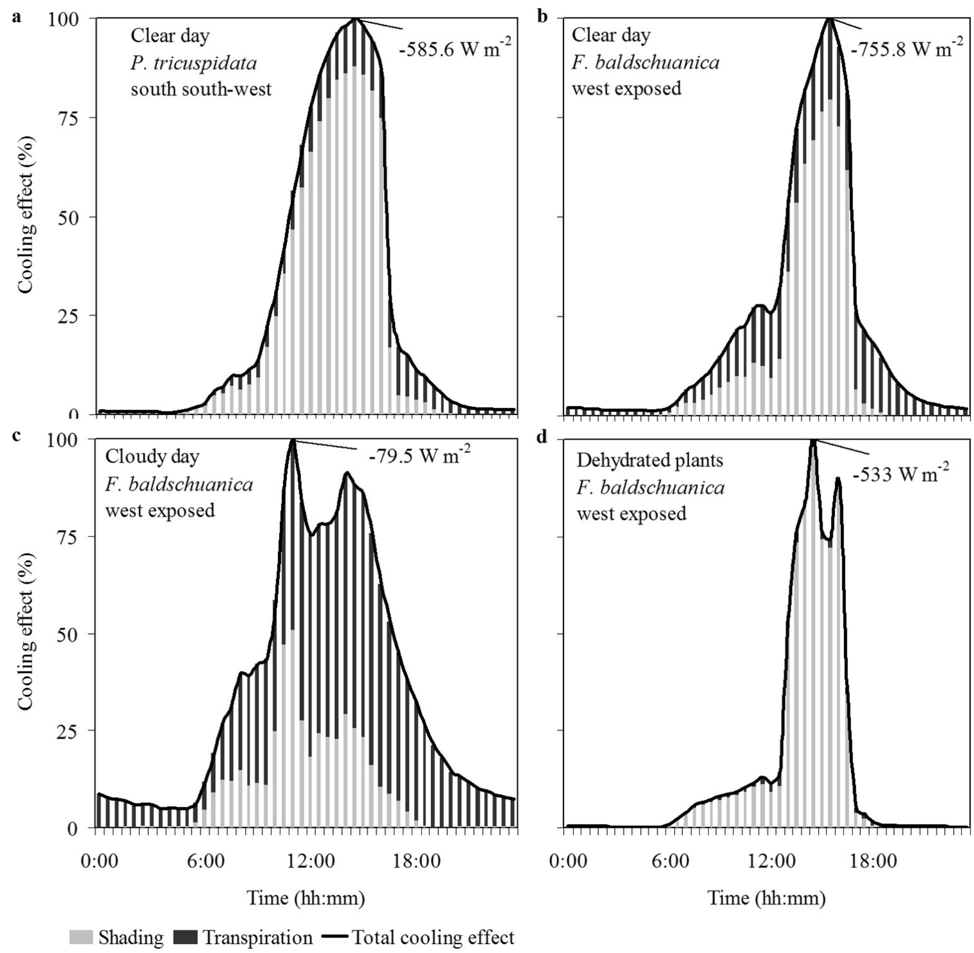

Fig. 8. Total cooling effect (transpiration + shading) as well as share of transpiration and shading on this cooling effect, each in relation to the maximum cooling effect of the day, for (a) a south south-west exposed facade greened with *Parthenocissus tricuspidata* on a clear summer day (2nd August 2013), (b) a west exposed facade greened with *Fallopia baldschuanica* on a clear late summer day (3rd September 2014), (c) a cloudy day (*F. baldschuanica*) (12th September 2014) and (d) plants under drought-stress (*F. baldschuanica*) (18th September 2014).

– sealed, compacted and providing only limited rooting volumes – the availability of such high water amounts can be critical on hot summer days. This corresponds to the authors' observation that autumnal colouring of *P. tricuspidata* occurs earlier in the city centre than in the outskirts. In contrast, we observed premature senescence and fall of leaves for a north oriented *F. baldschuanica* in beginning in October 2014, while the irrigated one at site C showed autumn foliage beginning only at the 20th November 2014 (derived from daily photos).

Table 1
Mean, maximum and minimum daily sap flow rates of *Parthenocissus tricuspidata* (2nd to 15th August 2013), *Hedera helix* (1st to 6th August 2014) and *Fallopia baldschuanica* (2nd to 15th September 2014) based on leaf area (LA) and wall area (WA).

	Per LA ($L\,d^{-1}\,m^{-2}$)	Per WA ($L\,d^{-1}\,m^{-2}$)	Per WA ($W\,m^{-2}$)
Parthenocissus tricuspidata ($n = 14$, wall leaf area index (WLAI) = 1.9)			
Daily sap flow			
Mean	0.5	0.9	26.6
Maximum	0.7	1.3	35.4
Minimum	0.4	0.7	19.9
Hedera helix ($n = 6$, WLAI = 3.0)			
Daily sap flow			
Mean	0.5	1.6	45.6
Maximum	0.6	1.7	49.5
Minimum	0.4	1.2	32.8
Fallopia baldschuanica ($n = 14$, WLAI = 3.0)			
Daily sap flow			
Mean	0.5	1.4	39.3
Maximum	0.8	2.3	65.6
Minimum	0.2	0.7	19.6

In preliminary studies on climbers it was confirmed that their cooling effects can turn into the opposite, namely leaf surfaces warmer than ambient air temperatures when they were not irrigated sufficiently. Furthermore, a drought-stressed plant showed up to 2.5 °C higher leaf temperatures than a well-watered plant [33].

For *H. helix* at site B, the daily transpiration rates varied from 1.2 to 1.7 $L\,d^{-1}\,m^{-2}$ (WA) which corresponds to an energy equivalent between 32.8 and 49.5 $W\,m^{-2}$. In contrast, for *F. baldschuanica* the daily transpiration rates per WA were 0.7 to 2.3 $L\,d^{-1}\,m^{-2}$ which results to an energy conversion of up to 65.6 $W\,m^{-2}$. As a consequence for hot summer days, the provided water amount for *F. baldschuanica* must be at least 1.3 times that for *H. helix* and twice as high as for *P. tricuspidata*.

Please note that these irrigation demands are derived from sap flow measurements. Although the applied calibration method for the sap flow data is widely accepted and in use, there are hints that the derived transpiration rates are underestimated [e.g. 24]. Obviously, this also leads to some uncertainty in the statements on the contribution of shading and transpiration on the total cooling effect. Finally, the above stated water demands can only be rough estimates. However, they strongly indicate the need to irrigate facade greenings, if they should contribute to building cooling and urban climatic effects. This is another argument to consider facade greening as a form of artificial urban green with a high maintenance demand not only in pruning and service but also in irrigation.

4. Conclusions

Our study demonstrated cooling effects of facade greening through transpiration and shading. While the surface temperatures of the exterior and interior building walls were clearly decreased by the greening, no clear differences in ambient air temperature were measurable. Based on interior wall temperatures, we could show that facade greening is most effective during night-time, which is very relevant for the reduction of nocturnal indoor heat stress. However, we also demonstrated possible disadvantages through its insulation effect during the night. Therefore, we could show that the design of the facade greening has major impacts on cooling effects towards the street canyon and the building. Depending on the climatic aim of the facade greening, direct or indirect facade greenings are to favour.

The provided cooling effects on hot summer days mainly depended on shading, whereas a lower proportion was due to transpiration. Whether these differences in contributions of shading and transpiration for *P. tricuspidata* and *F. baldschuanica* on the total cooling effects were only plant specific or also due to the irrigation status or the meteorological conditions could not be completely assessed in this study and should therefore be further investigated. Facade greenings must be sufficiently irrigated with up to $2.5\,\mathrm{L\,d^{-1}\,m^{-2}}$ (WA) in order to be able to provide their cooling performance.

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