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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