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What's 'cool' in the world of green façades? How plant choice influences the cooling properties of green walls

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Abstract:

Green walls provide an option for reducing the thermal load on buildings, reducing the requirement for mechanised air conditioning and helping to mitigate urban heat islands. The range and extent of benefits can vary with green wall typology. This research investigated green façades utilising wall shrubs and climbing plants to reduce air temperature adjacent to, and surface temperatures of, brick walls. Artificial wall sections were used to provide replicated data sets in both outdoor and controlled environmental conditions. During periods of high solar irradiance outdoors, the presence of live *Prunus laurocerasus* plants placed against walls significantly reduced air and surface temperatures compared to blank walls, but also in comparison to excised (non-transpiring) plant sections. Largest temperature differentials were recorded mid-late afternoon, where air adjacent to vegetated walls was 3°C cooler than non-vegetated walls. *Prunus* also provided significant wall cooling in controlled environment studies, but was intermediate in its surface cooling capacity (6.3°C) compared to other species; *Stachys* and *Hedera* providing > 7.0°C cooling. When evaluated on a per leaf area basis, however, other species demonstrated greater cooling potential with *Fuchsia*, *Jasminum* and *Lonicera* out-performing others. Not only was it evident that different species varied in their cooling capacity, but that the mechanisms for providing wall cooling varied between species. *Fuchsia* promoted evapo-transpiration cooling, whereas shade cooling was more important in *Jasminum* and *Lonicera.* Plant physiology and leaf area/morphology should be considered when selecting species to maximise cooling in green wall applications.

Keywords:

Climbers, evapo-transpiration, green façade, shade, thermal performance, wall shrubs

Nomenclature

ANOVA	Analysis of variance
ETp	Potential evapo-transpiration
g_s	Stomatal conductance. Amout of moisture emitted from a given area of leaf [µmol m^{-2} s^{-1}]
h	Time [hours]
I_s	Solar irradiance as measured on a horizontal plane [W m^{-2}]
k	Thermal conductivity [W m^{-1} K^{-1}]
lbh	Length, breath, height
LAI	Leaf area index. Ratio of leaf area to horizontal plane area
LSD	Least significant difference
N	North aspect
n	Number of replicates
n_c	Cloud cover, based on sky area divided by eighths [oktas]
P	Probability, lower values represent greater confidence
r.h.	Relative humidity (%)
S	South aspect
SLA	Specific leaf area. The density or thickness of a leaf [mm^2 mg^{-1}]
Tp	Temperature reduction due to plant and trough
Tp_{et}	Temperature reduction due to evapo-transpiration of plant
Tp_{sh}	Temperature reduction due to shade of plant
Tm	Temperature reduction due to evaporation from media / soil
$U2$	Wind speed at 2 m height
WLAI	Wall leaf area index. Ratio of leaf area to vertical wall area

1. Introduction

Green walls are a component of urban green infrastructure and contribute to a range of ecosystem services [1] including, habitat provision for urban biodiversity [2], intercepting precipitation and reducing run-off rates [3], screening out aerial particulate matter and improving air quality [4], attenuating noise [5,6], contributing to psychological well-being [7] and improving the aesthetics of the cityscape [8]. A further role is their potential to reduce urban air temperatures helping to mitigate urban heat island effects, and lower surface temperatures of buildings thereby reducing the reliance on mechanised air conditioning [9].

The role of green infrastructure in city cooling, reducing energy loads on buildings and improving human thermal comfort has warranted much attention over the last two decades [10], largely driven by concerns over climate change [11] and urban expansion [12]. Different forms of green infrastructure have been studied, including urban forests [13], street trees [14], parks [15], turf-grass [16], green roofs [17], gardens [18] and green walls [4] although their relative contributions and inter-relationships are perhaps less easy to discern. Even in a temperate climate increasing the proportion of green infrastructure by 10% could reduce mean air temperatures in the urban matrix by 2.5^{o}C, thereby reducing the frequency and magnitude of urban heat island events [19]. Vegetative cooling can replace energy used in mechanised air conditioning and help off-set a building's carbon budget [20]. For example, Kolokotroni et al. [21] comparing energy consumption in the UK during warm weather found that offices within well-vegetated locations did not need mechanised air conditioning to maintain internal temperatures < 24^{o}C, whereas those without local green infrastructure were reliant on it. Akbari et al. [22] estimated that additional urban planting in the USA could save up to 20% of national energy use due to reduced demand for air conditioning. Similarly, the strategic placement of four 'shade' trees per house could reduce annual carbon emissions by 41,000 tonnes per city [23].

Within any given form of green infrastructure, the predominant plant type and interactions with other factors such as soil moisture content are likely to strongly influence the cooling potential. Even the mechanisms by which plants provide cooling may vary: shading, evapo-transpiration, modifying air flow and promoting insulation layers of still ('dead') air within the building envelope, absorbing solar irradiance (I_s) (principally short-wave) and converting into biomass, and altering the albedo of land surface. Relative contributions of these cooling mechanisms will depend on plant form, species, canopy cover, moisture availability, seasonality and plant vigour. Shading is frequently quoted as the most significant aspect of plant cooling, suggesting that the greater the cover/volume of foliage the more effective the cooling [24-26]. In their study on trees (principally sites with 50-70 year-old *Ficus* spp.), Shashua-Bar and Hoffman [27] indicated that direct shading accounted for most of the cooling capacity under the canopy of a tree (80%) with evapo-transpiration having significant, but less influence. Evapo-transpiration, however, has greater significance in reducing air temperatures in the wider locale surrounding the tree [28]. Cooling effects of street trees have been recorded up to 100 m from their canopies [27]. Vegetation which is evapo-transpiring is also photosynthesising, in other words absorbing I_s and converting it to photochemical energy which would otherwise be absorbed and reflected back as infra-red radiation. Photosynthetic inefficiencies however, mean that a proportion of irradiance captured by the leaf can still be lost as heat, e.g. 40-60% depending on plant species and prevailing environmental conditions [29].

Compared to trees and grass, the role of green walls in contributing to building and aerial cooling has received detailed attention only comparatively recently [30,31] and few studies have used replicated treatments. Moreover, there is still limited information on the most appropriate type of green wall to employ or the plant species to use. Green walls tend to be divided into different categories. 'Green façades ' where plant-root balls are placed in the ground or in pots and the shoots grown up the side of a building; these usually comprise wall-shrubs, perennial climbing plants (vines) or annual climbing species. Climbing species can either fix themselves to walls through morphological features such as leaf tendrils, adhesion pads or aerial roots, or can be trained up a trellis or other framework against the wall. 'Living walls' in contrast, support plants that either root into the wall or have cells of substrate embedded in/on the wall. These cells or compartments are often supplied with water and nutrients through artificial irrigation/fertigation systems. A third designation is also used – 'biowalls'. These are similar to living walls but tend to be frequently designed to improve indoor air quality and humidity; they can be composed of microorganisms or populations of primitive plants (e.g. Bryophyta) as alternatives to higher plant communities.

The value of green walls to cool buildings has recently been cited for climatic zones with warm or hot summers. Living wall systems in China were shown to reduce exterior wall temperatures by a maximum of 20.8^{o}C, and interior wall by 7.7^{o}C [31]. Air layers between wall and vegetation were on average 3.1^{o}C cooler than ambient air [31]. Most studies have focussed on surface wall temperatures, with maximum differences between vegetated and non-vegetated cited as 11.6^{o}C Singapore [32], 18^{o}C Japan [33], 1.9^{o}C to 8.3^{o}C Greece [34], 15.2^{o}C Spain (35) and 12 to 20^{o}C Italy [36]. Further studies in Japan showed maximum temperature differences between vegetated and non-vegetated walls varied between plant species, with cooling maximums recorded as 11.3^{o}C *Ipomoea tricolor*, 7.9^{o}C *Canavalia gladiata*, 6.6^{o}C *Pueraria lobata,* 4.1^{o}C *Momordica charantia* and 3.7^{o}C *Apios americana*; although some of the differences were explained by different percentages of canopy cover over the wall, rather than any other trait [37].

Of the few studies implemented in temperate climates, research in the Netherlands showed that a green façade directly attached to a wall provided an average 1.2^{o}C cooling to surface temperatures. On another wall in a different location, providing an air gap between the façade and the wall provided 2.7^{o}C cooling compared to bare walls [38]. Repeated measurements were made at these walls, but the walls themselves were not replicated. Indeed, as most researchers are dependent on existing green walls *in situ* on buildings, opportunities to collect data from replicated treatments within the one location have been limited.

Despite the increasing evidence for green walls to improve the thermal performance of buildings in warm climates, the advantages are still less clear in more temperate zones with lower summer solar intensity, not withstanding climate change models and increased urbanisation [12]. Policy makers are still reluctant to endorse the use of green walls, due to a lack of replicated data sets for temperate scenarios, along with concerns that some green wall systems do not meet other sustainability criteria (wasteful in terms of water, nutrients and energy, e.g. to pump irrigation water around the wall [39]).

The aim of this research was to determine the performance of green façades in the temperate maritime climate of the UK, using replicated brick walls. These were used to mimic the walls of brick terrace houses, typical of inner-city housing stock in many UK cities. Due to temperature differentials being less than in warmer climates, treatments were replicated to increase statistical robustness. Similarly, we specifically chose a green façade over a living wall system to help offset any requirements for water and nutrients to be pumped around the wall, and to use a simple design that readily translates into practice in a domestic setting. Likewise, comparisons were made between wall shrub or climbing plants that are commonly used as garden or landscape plants, and which could be used in retro-fitting scenarios for older housing stock. Our objectives including understanding better the influence of plants on air temperature adjacent to a wall, as well as how species choice affected wall surface temperature when thermal energy was applied consistently under controlled environmental conditions. Although our use of replicated single walls outdoors, and controlled environments indoors were unlikely to fully represent the thermal properties and air currents found around buildings *in vivo* these approaches were considered advantageous in attempting to reduce any bias associated with specific individual buildings and associated micro-climates.

2. Material and Methods

2.1. Experiment 1. Air and surface temperatures of walls in situ *as affected by* Prunus laurocerasus

Brick walls were constructed outdoors at University of Reading, UK, using a standard housing brick ('Hadley's Red Brindle' 215 x 103 x 65 mm lbh; thermal properties: $k = 0.67$ Wm^{-1} k^{-1}, Blockley's Brick Holdings PLC, Telford, UK). Wall sections were 2.4 m long x 1.2 m high with a cavity space of 60 mm (Fig. 1). Individual sections were placed 1.2 m apart with a polystyrene infill (2.4 x 0.075 x 1.2 m lbh) used to thermally isolate each section of wall from its neighbour. Two rows were constructed, set 4.7 m apart, with 5 separate wall sections in each row. Walls were aligned to provide a north facing (N) and south facing (S) aspect to each wall. Bricks were laid in a stretcher bond using lime mortar (lime and local yellow quartz building sand). The basal layer of bricks was laid on grey concrete slabs (0.68 x 0.50

x 0.04 m lbh) with a 'damp course' layer (polypropylene tape 1.05 mm thick) incorporated above the basal layer of bricks. A Hobo H21 weather station and data logger (Tempcon Instruments Ltd. Arundel, UK.) was located in the centre of the two parallel lengths of wall and was used to record ambient air temperature (dry bulb; sensor located 2 m above ground within Stevenson screen; accurate to +/- 0.2°C), humidity (S-THB-M002 smart psychrometer with accuracy of +/- 2.5% from 10 to 90% r.h.), precipitation (duration and depth using a tipping bucket mechanism with accuracy of +/- 1% per 20 mm h^{-1}), irradiance I_s (silicon pyranometer 2 m above ground, measured over spectral range of 300 to 1100 nm; accurate to +/- 10 W m^{-2}), wind speed *U2* (anemometer located 2.5 m above ground measured speed per second, accurate to +/- 1.1 m s^{-1}), wind gust (fastest 2 s gust during 10 min logging interval) and wind direction (wind vector measured every 3 s; accurate to +/- 5°). Mean values for 10 min intervals were calculated.

Air temperature (Hobo Pro V2 External Temperature Sensors) was also recorded 80 mm from the exterior skin of each wall section using Stevenson's screens fixed to the wall and 400 mm above concrete slabs, and located on both the N and S aspect of each wall. Temperature sensors were accurate to +/- 0.2°C and calibrated every 3 weeks.

Plants of *Prunus laurocerasus* (an evergreen shrub with waxy, glabrous leaves) were grown in 20 L pots using a media comprising 60% John Innes compost, 20% peat, and 20% perlite, and were pruned prior to experimentation to provide a foliage canopy of approx. 0.9 x 1.2 x 0.5 m lbh. This treatment (*Prunus)* comprised of 4 plants being placed in front of each aspect of a wall section (i.e. 8 plants around each wall section with 4 walls being used in total). The central stem of each plant was placed 175 mm (pot diameter 350 mm) from the wall to ensure foliage did not interfere with air movement around the Stevenson screens. For an additional 3 walls, pots containing growing media were placed in equivalent locations (*Pot+media*), to ascertain heating/cooling effects due to the pot/damp media. In the final 3 walls, no pots or plants were placed in front of the walls (*Control*). To help avoid bias due to specific locations, the treatments were re-randomised across the walls sections every 10 days during experimentation. Plants were irrigated with 4 L of water per day to ensure pots retained enough water to optimise evapo-transpiration. To avoid any direct effects due to variations in moisture in the locality of the walls, non-planted pots and bare walls were also ‘irrigated’ with equivalent volumes of water.

Air temperatures at the central weather station (ambient) and within the vicinity of the wall (wall) were recorded every 10 min from 18th Aug until 19th Sep, 2009. During this period six individual days were identified where there was > 5 h of continuous $I_s > 120$ W m^{-2}, $U2 \leq 3$ m s^{-1} (calm to light breezes) and no precipitation. These days were used to provide a sub-set of data representing the warmest periods. (No consistent temperature differences in wall temperatures were noted during days defined as overcast [cloud cover $n_c = 8$ oktas] or with precipitation). Data are depicted for diurnal trends between 8.00 and 23.30 (inclusive) with values 10 min before, on and 10 min after each half-hour interval being used to provide mean values for each wall/location. Data sets were used to compare mean temperatures for each half-hour interval (6 per wall) and mean daily air temperature (192 readings per wall i.e. 32 half-hour temperature recordings x 6 days). Analysis of variance (ANOVA) was carried out using Genstat 13. (Rothamstead Research, Harpenden, Hertfordshire, UK) taking account of the unbalanced design (4 reps for one treatment, 3 reps for the others) and ensuring the variance in the data was homogenously distributed. Where mean temperatures are depicted as a time course, least significant difference LSD values ($P = 0.05$) are portrayed hourly for clarity. In addition to air temperatures, wall surface temperatures were recorded at specified times and under a range of climatic conditions. This was accomplished using a Thermal Imaging Camera (NEC Thermo Tracer TH7800, NEC infra-red technologies Ltd., Tokyo, Japan; -20 to 250^{o}C range with 0.1^{o}C resolution [at 8 - 14µm]), with plants being temporarily removed to determine the brick temperatures when screened by plants (temperatures recorded within 30 s of plants being moved; and all walls recorded within 5 min; Fig. 2). Thermal images were recorded for each wall. The camera was calibrated to an emissivity of 0.95 to provide a compromise between the emissivity of brick (0.93) and plants (0.94 - 0.98), and to minimise reflected infrared via surface albedo. The mean temperature of individual walls was determined by taking the mean of a random sample of 20 data points spread across the wall area of each image. On each occasion, the mean value of each wall was then used in ANOVA to determine any treatment effects on wall temperature.

2.2. *Experiment 2. Air and surface temperatures of walls* in situ *as affected by intact and excised stems of* Prunus laurocerasus

This experiment aimed to determine relative insulation effects due to live, intact plants and excised (dying) stems (i.e. how much was cooling affected by shade and evapo-transpiration compared to just shade alone). The format was similar to Experiment 1, but treatments comprised live plants as before (*Prunus*), excised stems inserted into media within a pot (*Excised*) and pots without any plant material as before (*Pot+media*). Replication was 4, 3 and 3 walls respectively. Excised stems were green at the commencement of the experiment (20 Sep. 2009), but had turned dull grey/green by the termination of the experiment (3 Oct. 2009). These cut stems were assessed for stomatal conductance (g_s) 24 h after cutting and there was negligible transpiration evident ($g_s < 5\%$ of intact plants). The excised stems were arranged within their 20 L pots to provide a foliage canopy of similar density to those of intact plants (10-15 main stems comprising 80-100 fully expanded leaves in total). The high lignin content and thick epidermis of leaves of this species resulted in those within the *Excised* treatment retaining their overall geometry, although some leaves tended to ‘droop’ after 4-5 days following cutting (bending at the petiole due to loss of turgor). Locations of treatments were re-randomised and altered after 7 days. Temperature data between the 3 treatments was assessed as before, again restricted data to six days with the greatest I_s. As with Experiment 1, data were used to compare treatment effects for daily mean air temperatures and for each half-hour interval. Wall temperatures were recorded via infra-red thermography as before.

2.3. Experiment 3. Wall temperature as affected by vegetation type within controlled environments.

The influence of different plant species in providing cooling was investigated using model brick walls and a point heat source housed within controlled environment facilities. This experiment was carried out in 3 growth cabinets (1.37 x 1.37 x 1.14 m lbh, 'Saxcil', National Institute of Agricultural Engineering, Silsoe, UK) with 2 small brick walls (0.59 x 0.10 x 0.66 m lbh and spaced 0.14 m apart) constructed in each. Walls were composed of Hadley’s Red Brindle’ bricks but without mortar or cavity spaces and 3 temperature probes (Hobo Pro V2 external thermal sensors: Tempcon Instrumentation, Arundel, Sussex) were inserted between individual bricks on the front face of each wall (to a depth of 10 mm); to provide wall surface temperature readings. A heat source was provided in each cabinet by placing an aluminium 'agricultural pig lamp' (0.2 m dia. 300 W incandescent tungsten bulb) 0.88 m in front of, and equidistant, to the 2 walls. In addition, supplementary lighting for plant growth was provided via 53 x 58 W fluorescent (Sylvania Warm White -F58W/129T8) and 30 x 15 W incandescent bulbs per cabinet (340 µmol m^{-2} s^{-1}); these being situated in the cabinet roof. Fans built into the floor apertures helped avoid heterogeneous air temperature profiles within the cabinets. Silver foil baffles placed over the floor grills were used to stop air blowing directly over the walls and plants.

Plants were planted in polypropylene troughs (0.60 x 0.21 x 0.17 m lbh, LBS Horticultural Supplies, Lancashire, UK) using the media outlined in Experiment 1 and grown in a glasshouse from June 2010 (at > 18°C with supplementary light between 16.00 to 21.00 daily, thus ensuring plants remained in growth and retained full leaf canopies during autumn). Six species were evaluated: - *Prunus laurocerasus*, *Jasminum officinale* 'Clotted Cream', *Hedera helix*, *Stachys byzantina*, *Fuchsia* 'Lady Boothby' and *Lonicera* 'Gold Flame' with 3 plants of one species inserted into each trough. The selection reflected a range of common woody perennial climbing or screening plant species as well as the evergreen *Prunus* used before. The silver, pubescent-leaved, semi-herbaceous *Stachys* was introduced to provide contrast in terms of leaf colour and structure, and which has previously been shown to have positive thermal insulation properties with respect to green roofs [40]. Six plant troughs were planted for each species, but prior to experimentation the foliage of plants in half of these was sealed with poly (1-acetyloxiethylene); proprietary name: PVA- 'Quick Dry Tile Sealant', B&Q, Southampton, UK) to inhibit transpiration both by blocking the stomatal pores and reducing cuticular conductance of water. (This was considered preferable to using cut stems as before, due to the tendency for leaves of some of the new species to become excessively contorted after excision from the parent plant). Preliminary studies indicated the PVA to be effective in inhibiting 96-98% of normal evapo-transpiration, and once dry, did not visually alter the light reflectance properties of the leaf.

Experiments were conducted between 1 Sep. and 17 Dec. 2010. Prior to placement in cabinets, plants were irrigated to container capacity then housed at 18^{o}C for 15 h (without light within a fourth cabinet). This helped stabilise the temperature of plants/troughs/media and ensured plants entered the cabinet at comparable temperatures on each occasion. Heat lamps were switched on in the experimental cabinets 7 h before plants/troughs were introduced, resulting in the wall temperatures stabilising at 26.5 +/- 1^{o}C. (Preliminary data suggested walls reached a maximum equilibrium temperature after approx. 5 h). Planted troughs were introduced and placed directly in front of one of the walls in each cabinet, with troughs with moist media but no plant placed in front of the alternative wall as a control (i.e. cooling effect due to media alone). Foliage was pinned to the walls using plant ties, ensuring the foliage covered the wall in a relatively uniform manner. Temperature in each sensor was recorded every 10 mins, and temperature profiles of walls with and without plants monitored for 10 h. Before and after each experimental run, troughs were weighed to determine moisture loss during exposure to the heat/light source.

For each species, 3 cabinets were used concurrently and the experiment repeated for each individual trough (i.e. 2 blocks of time with n = 3 on each occasion; on the repeat run the position of the planted trough and control trough was altered between the 2 walls). After the process was completed for non-sealed plants of each species, it was repeated with specimens sealed with PVA. In this way temperature profiles and water loss data could be assessed for: a = transpiring plant and media, b = non-transpiring plant and media, and c = media alone. This allowed calculation of the cooling effect on the wall (^{o}C) due to total cooling of a planted trough [Tp = a], plant evapo-transpiration [Tp_{et} = a-b], shade [Tp_{sh} = b-c] and media evaporation in the planted troughs [Tm = a-((a-b)+(b-c))] . On completion of experiments, plants were destructively harvested and measured on a per trough basis for leaf number, total leaf biomass (dry weight), mean leaf dry weight, mean specific leaf area, mean leaf thickness (individual leaf areas/leaf biomass) and total stem biomass (dry weight). Wall leaf area index (WLAI) was calculated as a ratio of total leaf area compared to exposed wall area and used to estimate the density of the foliage covering the wall. Leaf areas were obtained using Area Meter Model E400, Delta T

Devices, Cambridge, UK. Leaves and stems were excised and dried at 70°C for 48 h in an oven (Weiss Gallenkamp, Loughborough, UK) before being weighed.

A summary of experimental details is provided in Tables 1a and 1b.

3. Results

3.1. Experiment 1. Air and surface temperatures of walls in situ *as affected by* Prunus laurocerasus

During days of high I_s (> 5 hours of continuous irradiance > 120 W m^{-2}) mean daily air temperature recorded at the wall surface behind *Prunus* foliage was significantly less than that of the *Pot+media* treatment or the blank walls of the *Control*, regardless of orientation (Table 2). Indeed, the air at the south side of vegetated walls was significantly cooler than air adjacent to the north side of non-vegetated walls. In contrast to *Prunus,* the *Pot+media* treatment did not significantly enhance cooling compared to the *Controls*.

When half-hourly mean air temperatures are compared over the course of the day (Fig. 3), the temperature with the *Prunus* treatment was significantly cooler than *Pot+media*, on both orientations from 11.00 to 18.00. The largest differential on the southern aspect was associated with 16.00, where air adjacent to vegetated walls (*Prunus*) was almost 3°C cooler on average than non-vegetated walls. From 19.00, there was no significant difference in the air temperatures of any of the treatments. Thermal images of wall and leaf surface temperatures confirmed the cooling effect of the vegetation. For example on a warm day with high solar irradiance 19th Aug. 2009 (ambient temperature = 24.1°C, I_s = 693 W m^{-2} and $U2$ = 0 m s^{-1} recorded at 15.00), mean temperatures on the southern aspect were; surface of plant foliage = 27.6°C, wall behind foliage (*Prunus*) = 24.0°C, *Control* wall = 33.9°C and *Pot+media* wall = 33.2°C; LSD = 0.81 (P = 0.05) d.f. = 12.

3.2. Experiment 2. Air and surface temperatures of walls in situ *as affected by intact and excised stems of* Prunus laurocerasus

Mean daily air temperature behind intact stems of *Prunus* was significantly cooler than that behind excised stems on the south aspect, but not the north aspect

(Table 3). Both *Prunus* and *Excised* treatments reduced air temperatures adjacent to the walls compared to *Pot+media*, but only significantly on the south side. Diurnal trends also demonstrated that intact stems (*Prunus*) kept the air around the south sides significantly cooler than the equivalent aspect of *Excised* or *Pot+media* treatments from approx. 9.00 to 16.00 per day (Fig. 4). *Excised* was significantly cooler than the *Pot+media* treatment on the southern aspect for much of this time too. On the northern side, there was no significant difference between *Prunus* and *Excised* treatments until 15.00, at which point the air temperature behind *Excised* stems became significantly higher. During the evening period, however, air temperatures adjacent to the north side of the *Prunus* walls were warmer than other treatments, being marginally significantly different to *Excised* north, at 20.00.

Surface temperatures of the walls showed similar trends as before i.e. generally cooler behind the *Prunus* treated walls compared to the walls of the *Pot+media* treatment. During periods of high I_s, wall surface temperatures were often cooler too behind the live *Prunus* foliage compared to the *Excised* foliage e.g. 23 September at 14.30 southern aspect wall temperatures were 20.7 and 22.0^{o}C respectively, LSD ($P = 0.05$) = 0.62 d.f. = 12.

3.3. Experiment 3. Wall temperature as affected by vegetation type within controlled environments

Each species significantly reduced wall temperature compared to control troughs with growing medium alone ($P \leq 0.001$). This was the case irrespective of whether the plants had been sealed or not, but there was an additional cooling effect when plants were not sealed; differences being significant ($P \leq 0.001$) across all species examined. In non-sealed plants the highest rate of overall cooling (Tp) was achieved by *Stachys* and *Hedera* (7.6^{o}C and 7.3^{o}C cooler than controls, respectively). These were significantly greater temperature reductions than those achieved by *Lonicera*, *Fuchsia* (both 5.5^{o}C) and *Jasminum* (4.3^{o}C) (Fig. 5). *Prunus* was intermediate in its ability to cool the wall (6.3^{o}C).

By comparing data from sealed and non-sealed plants, however, it was apparent that the mechanisms for cooling the wall varied between species. *Hedera, Lonicera* and *Jasminum* were largely reliant on shading to provide their cooling effects, whereas a greater proportion of the cooling from *Fuchsia* was associated with evapo-transpiration. *Prunus* and *Stachys* cooled through equal contributions of shading and evapo-transpirational cooling (Fig 5.). Moisture loss directly from the medium provided approximately 0.5 to 1°C of cooling – not significantly different between species.

Destructive harvesting of the plants revealed that *Hedera* had the greatest number of leaves present (mean 460 leaves per trough), significantly greater than any other species ($P \leq 0.001$) (Table 4). This corresponded to both the greatest leaf and stem biomass present, but *Prunus* also had high leaf and stem biomass values despite considerably fewer individual leaves (Table 4). *Prunus* and *Stachys* both had the lowest specific leaf area indicating their leaves were significantly thicker than all other species ($P \leq 0.001$); twice as thick as *Lonicera* (Table 4), which possessed leaves that were significantly thinner than the other species, ($P \leq 0.001$). *Hedera, Fuchsia* and *Jasminum* were mid-range.

When the combined leaf areas per species were compared to the wall area, it demonstrated that *Hedera* provided the highest density of wall foliage, with a large proportion of leaves overlapping – in some cases up to 5 leaves deep (Fig. 6). *Stachys* and *Prunus* also were effective at covering the wall, although these leaves were evenly distributed with less self-shading between the leaves. In contrast, the WLAI values for *Fuchsia*, *Jasminum* and *Lonicera* (i.e. < 1) reflected that the canopies of these plants were not fully covering the wall (Fig. 6).

Re-evaluating temperature data based on the WLAI resulted in a re-ordering of species ranking in terms of cooling potential (compare Fig. 7 to Fig. 5). Normalised for leaf area, *Fuchsia* achieved the highest overall cooling (Tp) of 9.4°C, significantly higher than any other species (Fig. 7). *Jasminum* and *Lonicera* also provide effective cooling with total temperature reductions calculated as 7.5°C and 7.1°C, respectively. This is in contrast to *Hedera* with a cooling potential of only 1.4°C, most of which is associated with leaf shading (Fig. 7).

4. Discussion

Screening model walls with plants provided localised cooling and significantly reduced air temperatures adjacent to the walls, as well as wall surface temperatures.

During warm days (≥ 5 h of continuous irradiance ≥ 120 W m^{-2}) the presence of living *Prunus* specimens significantly reduced air temperatures compared to blank control walls from 11.00 to 18.00 per day on both north and south orientations. During the warmest periods, air temperatures were 3°C cooler in the presence of vegetation. At such times, wall surface temperatures behind plants could be as much as 9.2°C (vs Pot+media) or 9.9°C (vs blank wall) cooler. The results are all the more remarkable in that the non-vegetated or Pot+media walls were irrigated at the same frequency as the planted walls. This suggests the additional cooling influence conferred by plants relates to their ability to better 'distribute' cooling moisture vapour around a wall, compared to simply wetting the wall locality. Although the cooling influence of water is recognized [28], few previous studies have controlled for its presence in this way. This, in combination with the implementation of structured, replicated experiments outdoors, albeit without using the walls of functional buildings, adds weight to the evidence that plants provide a cooling effect around buildings. Air temperature differences in this research are consistent with those found by Chen et al. [31] in a hot humid region of China. Wall surface temperatures differences were comparable to Greece [34] although somewhat less than differences recorded in other warm climates [33-36]. Nevertheless, the data suggests that green façades are a viable form of building cooling for temperate climates. Although the number of warm days experienced may be less than in warmer climatic zones, they do provide significant cooling influence when I_s exceeds 120 W m^{-2} for a number of hours. Therefore, the data indicates the use of green façades can be justified as a retrofit option for older brick housing stock in the UK.

Excised (dead stems) of plants also provided wall cooling, but not to the same extent as those plants that were transpiring. The placement of a pot with moist growing media seemed to have little impact on the micro-climate of the wall, suggesting most of the cooling was attributable to the plant itself. Thus, as discussed above, live transpiring plants have a positive role to play in reducing the heat loads on buildings during the warmest part of the day. It should be noted, however, that after 19.00, air temperatures behind live plants could be warmer than that of blank walls or even dead excised stems, although differences were not always statistically significant. These temperature differences may in part relate to a buffered thermal capacity associated with higher moisture content of live compared to dead stems, or that dead stems had some alteration in their physical structure that influences heat transfer from the wall. A small number of leaves (≤ 5% of total) on dead stems demonstrated some curling and wilting by the end of the experiment.

During cold weather scenarios, retaining warmth around a building envelope is advantageous (e.g. trapping I_s in winter and detaining heat loss during the evening could reduce/delay the requirement for internal heating) [38,41]. In a summer heat wave though, blocking heat loss from the building in the evening would be a drawback as interior temperatures at night can particularly impact on human thermal comfort [42]. Although our data for evenings/night between vegetation clad and blank walls were often borderline in significance, we did not test for this 'heat retention effect' under more extreme heat wave scenarios, where blockage of heat loss could be more critical. The phenomenon of warmer air behind green façades during the evening/night period has been recorded elsewhere [31], but perhaps warrants further attention with respect to human thermal comfort at night.

Although the results confirm previous work on the cooling benefits of green walls in general, what is less evident is that choice of species may have a strong influence of the form of cooling (shade v evapo-transpiration), and that degree of cooling can be strongly influenced by individual plant characteristics. In essence, not all plant species provide cooling to the same degree or by the same means. The use of controlled environments with an artificial, but reproducible heat source proved useful in determining the thermal cooling properties of different plant species. In these experiments, greatest overall cooling was associated with *Hedera* and *Stachys.* This was largely attributable to the greater number of leaves present with these species and their propensity to form a dense foliar canopy in front of the wall. This resulted in a 7°C differentiation in surface temperatures compared to non-screened walls. Comparisons on temperature profiles between specimens with sealed and non-sealed leaf surfaces suggest that *Hedera* provided cooling primarily through a shading effect, by blocking infra-red irradiance; in contrast cooling influence with *Stachys* was associated with both shading and localised cooling via evapo-transpiration. With this silver, pubescent-leaved species, it is feasible that there was some cooling attribute linked with greater reflection of irradiance [43].

Comparing sealed and non-sealed leaves provided valuable information on how localised cooling was being conferred. Shading provided a greater cooling influence than evapo-transpiration in *Jasminum* and to some extent *Lonicera*, as well as in *Hedera*. Cooling mechanisms with *Stachys* and *Prunus* was equally attributable to shading and evapo-transpiration. In contrast, *Fuchsia* was strongly reliant on evapo-transpiration, with this accounting for approx. 3^{o}C of the total cooling compared to 1.5^{o}C associated with the shade effect. In addition, in outdoor experiments (Exps 1 and 2) there was significantly cooler air temperatures on the south of the vegetated walls compared to the shaded north side of un-vegetated walls, and there were significantly cooler air temperatures behind live plants compared to dead plant material, suggesting that evapo-transpirational cooling was a significant cooling factor in *Prunus* outdoors, agreeing with previous studies [28,30]. However, these experiments have shown that a number of additional factors, particularly wall leaf area index and plant morphology can also significantly affect overall cooling performance.

When accounting for different leaf cover patterns between the species (Fig. 7), it was evident that greatest cooling *per unit of leaf area* was associated with *Fuchsia*. Not only did this species cool effectively through evapo-transpiration, it had greater shade cooling on a per leaf basis than other species such as *Stachys*, *Hedera* and *Prunus*. As *Fuchsia* had a low wall leaf area index (WLAI), encouraging specimens to develop a thicker canopy may prove effective in enhancing the cooling dynamics further. *Jasminum* and *Lonicera* also provided effective cooling when assessed on a per leaf area basis, and again the use of more mature specimens with thicker canopies may have greater potential for total cooling *in vivo* than our results based on relatively young specimens might suggest. As mentioned, cooling in *Jasminum* and *Lonicera* was associated with leaf shading being a dominant factor.

Increasing the density of foliage is considered to improve the cooling potential through providing greater shade [9,44,45] and plant species are often chosen that provide thick canopies, i.e. high (wall) leaf area indexes. The advantage of thicker canopies only seems to be partially true from the data in this study. *Stachys* had a significantly lower WLAI than *Hedera* (Fig 6.) yet comparable cooling ability (Fig. 5). Species that had relatively low WLAI values (0.6 to 0.8) namely, *Fuchsia, Jasminum*, and *Lonicera* provided higher shade (and comparable or greater evapo-transpirional) cooling when assessed on a per WLAI basis (Fig. 7) compared to those with higher WLAI, i.e. *Stachys, Prunus* and *Hedera*. The former species may combine the ability to provide shade and minimise gaps in foliage cover, whilst also possessing the capacity to arrange leaves that fully exploit available irradiance and also experience high vapour pressure gradients; both factors important in optimising evapo-transpirational cooling. Conversely, *Hedera* perhaps illustrates some of the negative effects of high leaf area. Despite possessing the largest dry leaf biomass, and over twice as many leaves per trough as any other species, it corresponded to the lowest cooling per WLAI (Fig. 7). This suggests shade cooling had reached a saturation point, with additional leaves providing no extra benefit [46].

Although WLAI was a useful tool to determine relative canopy cover/density between species, some care is required when interpreting the data. Mathematically a WLAI value of 1 is equal to complete cover of wall area with one layer of leaf. In practical terms, however, leaves overlap and sections of stems will be without leaf cover, so a WLAI = 1 does not necessarily equate to a uniform coverage of foliage across the wall. Indeed plants with WLAI < 1 could provide more shade than those with higher values, solely based on more uniform coverage of foliage and differences in leaf morphology. Care is also warranted when selected species based on cited leaf area indices (LAI) for individual species as these relate to canopy cover over the ground, i.e. a horizontal not vertical surfaces. Growth habit and leaf orientation will differ when plants grow up a wall, altering the shading dynamic.

The cooling attributed to ‘shade’ (Fig. 7) may not only relate to the interception of irradiance, but how incoming energy is dissipated. Leaf size is important in this respect. Although large leaves may intercept more irradiance than small ones and reduce the amount of direct solar irradiation the wall is exposed to, leaf size and morphology can influence other thermal aspects. Small and pinnate leaves stay cooler than larger leaves, as turbulence over the boundary layer between the leaf epidermis and the air is directly proportional to the size of the leaf, i.e. the smaller the leaf, the greater the flux over the leaf surface. This means the rate of surface convection, and in turn conductance of heat from the leaf structure, increases as leaves size diminishes [46, 47]. This cooling effect in small/pinnate leafs is well documented, but the link between these characteristics as a factor in plant selection for green walls is not. Effective ‘shade’ cooling with *Jasminum* (Fig. 7) therefore, may in part be due to its pinnate leaves which increase the shadow effect per leaf area, but also function like small leaves in respect to air and heat transport [47]. *Lonicera* and *Fuchsia* also have small individual leaves (approx. 50 x 20 mm), but *Fuchsia* did not demonstrate quite the same 'shade' influence (Fig. 5). In this case, however, cooling performance might be due to the arrangement of the leaves along the stem. *Lonicera* and *Jasminum* have leaves distributed along entire stem lengths, maximising shadow effect per leaf. *Fuchsia* in contrast, has leaves whorled in clusters regularly spaced along branches and hence presented larger gaps in shade cover.

Irrespective of leaves, the cooling influence of stems should not be overlooked. A network of stems may increase shading, but also affect air flux around the canopy e.g. aiding convection/conduction of heat, and increasing air turbulence by their physical presence [38]. They also conduct cool soil water through their xylem vessels in the transpiration stream. Thermal imagining in this study frequently indicated stems were cooler than adjoining leaves. The multiple-stem nature of many climbing plants, therefore, may add an important extra dimension to cooling potential, and theoretically be more effective than a single stemmed species, but this remains untested.

5. Conclusions

Wall shrubs and climbing plants provide significant thermoregulation around brick walls, and appear to be a feasible green wall system for retrofitting existing housing stock in temperate climates. Choice of plant species influences cooling potential. *Hedera* and the silver-leaved, semi-herbaceous *Stachys* might be best species to recommend for wall cooling based on the results presented here, but if other species increased the density of their canopy with time as they grow, they may actually provide better cooling potential, particularly if they are well irrigated and able to maintain consistent evapo-transpiration. Further evaluations are required, especially on species selection and management issues but green façades appear to provide a relatively simple solution to insulating older housing stock, and contributing to urban heat island mitigation.

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Table 1a Summary details of each experiment

Experiment	**1**	**2**	**3**
Wall material	Brick	Brick	Brick
Dimensions (m)	2.4 x 1.2	2.4 x 1.2	0.60. x 0.66
Environment	Outdoor	Outdoor	Env. Cabinet
Date	18/8-19/9, 2009	20/9- 3/10, 2009	1/9-17/12, 2010
Aspect	N & S	N & S	NA
Heat source	Solar	Solar	Electrical 300 W
Air temp. range	4 to 27^{o}C	5 to 24^{o}C	18 to 27^{o}C
U2 range	0 to 12.7 m s^{-1}	0 to 9.4 m s^{-1}	NA (fans < 2 m s^{-1})
r.h. range	55 to 92%	49 to 95%	64 to 86%
Treatment comparisons	Planted wall v Bare wall v Wall with pots & moist media	Planted wall (shade and ETp) v Wall with excised 'dead' plant (shade) v Bare wall	1. Planted wall v Wall with trough & moist media 2. Planted wall with leaves covered with PVA (no transpiration) v Wall with trough & moist media

Table 1b Summary details of each experiment (contd.)

Experiment	**1**	**2**	**3**
Species	*Prunus*	*Prunus* (live v excised)	*Stachys,* *Fuchsia,* *Jasminum,* *Hedera,* *Lonicera,* *Prunus*
Plants pre-treated	No	No	Yes – housed in glasshouse to retain foliage
Comparisons where data sets restricted:	Yes: $I_s = 120$ W m^{-2} > 5 h, $U2 \leq 3$ m s^{-1}, r.h. ≥ 66%	Yes: $I_s = 120$ W m^{-2} > 5 h, $U2 \leq 3$ m s^{-1}, r.h. ≥ 54%	No:
Initial wall temp.	NA	NA	26.5°C
Key measured parameters	Air temp – half hour mean (ambient and 80 mm from wall) Wall surface temperature (thermal image) Plant surface temperature (thermal image)	Air temp – half hour mean (ambient and 80 mm from wall) Wall surface temperature (thermal image) Plant surface temperature (thermal image)	Wall surface temp. Weight of trough, media & plant Leaf number, area, weight, dry weight Stem dry weight
Derived parameters	NA	NA	Change in temp: Tp Tp_{et} Tp_{sh} Tm SLA Leaf thickness WLAI

Table 2 Mean daily air temperatures of *Prunus*, *Pot+media* and blank *Control* wall treatments on North (N) and South (S) sides of walls. Data restricted to days with ≥ 5 h irradiance > 120 W m^{-2}, August to September 2009. Significance levels and LSD (*P* = 0.05) d.f. = 383 values for selected comparisons shown

Mean air temperatures (°C)		Selected comparisons	*P* value	LSD
Prunus N	17.9	*Prunus* N v *Prunus* S	0.026	0.28
Prunus S	18.2	*Prunus* N v *Pot+media* N	≤ 0.001	0.41
Pot+media N	19.1	*Prunus* S v *Pot+media* N	≤ 0.001	0.44
Control N	19.4	*Prunus* S v *Pot+media* S	≤ 0.001	0.37
Control S	19.4	*Pot+media* N v *Control* N	0.600	0.76
Pot+media S	19.5	*Pot+media* N v *Pot+media* S	0.143	0.45
		Control S v *Pot+media* S	0.779	0.75

Table 3 Mean daily air temperatures of *Prunus*, *Excised* (*Prunus* stems) and *Pot+media* treatments on North (N) and South (S) sides of walls. Data restricted to days with ≥ 5 h irradiance > 120 W m^{-2}, September 2009. Significance levels and LSD (*P* = 0.05) d.f. = 383 values for selected comparisons shown

Mean air temperatures (°C)		**Selected comparisons**	***P* value**	**LSD**
Prunus N	16.0	*Prunus* N v *Prunus* S	0.833	0.38
Prunus S	16.0	*Prunus* N v *Excised* N	0.947	0.45
Excised N	16.1	*Prunus* N v *Pot+media* N	0.053	0.42
Excised S	16.5	*Prunus* S v *Excised* S	0.050	0.46
Pot+media N	16.5	*Prunus* S v *Pot+media* S	≤ 0.001	0.46
Pot+media S	17.4	*Excised* N v *Pot+media* N	0.087	0.48
		Excised S v *Pot+media* S	0.023	0.49

Table 4 Physical parameters of different plant species (*Stachys-Sta, Fuchsia-Fuch, Jasminum-Jas, Hedera-Hed, Lonicera-Lon, Prunus-Pru*). LSD (*P* = 0.05) d.f. = 17

Per trough	*Sta*	*Fuch*	*Jas*	*Hed*	*Lon*	*Pru*	LSD
Mean No. leaves	219	158	135	460	190	185	51
Mean total leaf dry biomass (g)	72	20	22	206	20	128	24
Mean dry wt per leaf (mg)	332	128	165	447	103	698	61
Mean total stem dry biomass (g)	0	78	92	277	60	187	69
Spec. leaf area ($mm^2\ mg^{-1}$)	4.5	8.0	7.0	6.7	10.8	5.2	0.83

Figure 1. Layout for Exp. 1. Replicate wall sections were orientated in two rows, providing each section with a north and south aspect.

Key

A	Brick cavity wall, with insulated polystyrene sections between walls
B	Stevenson screen, with V2 temperature sensors 80 mm from wall surface
C	Hobo 21 weather station
D	*Prunus* walls
E	*Pot+media* walls
F	*Control* (bare) walls

NB treatment locations rotated during experiment to help avoid inadvertent positional bias

Figure 2. Wide angle thermal image from Exp 1. Plants were pulled back from the wall temporarily and high resolution thermal images of the wall section recorded (barred lines depict approximate location). Equivalent sections of non-covered walls also recorded, within 5 min period.

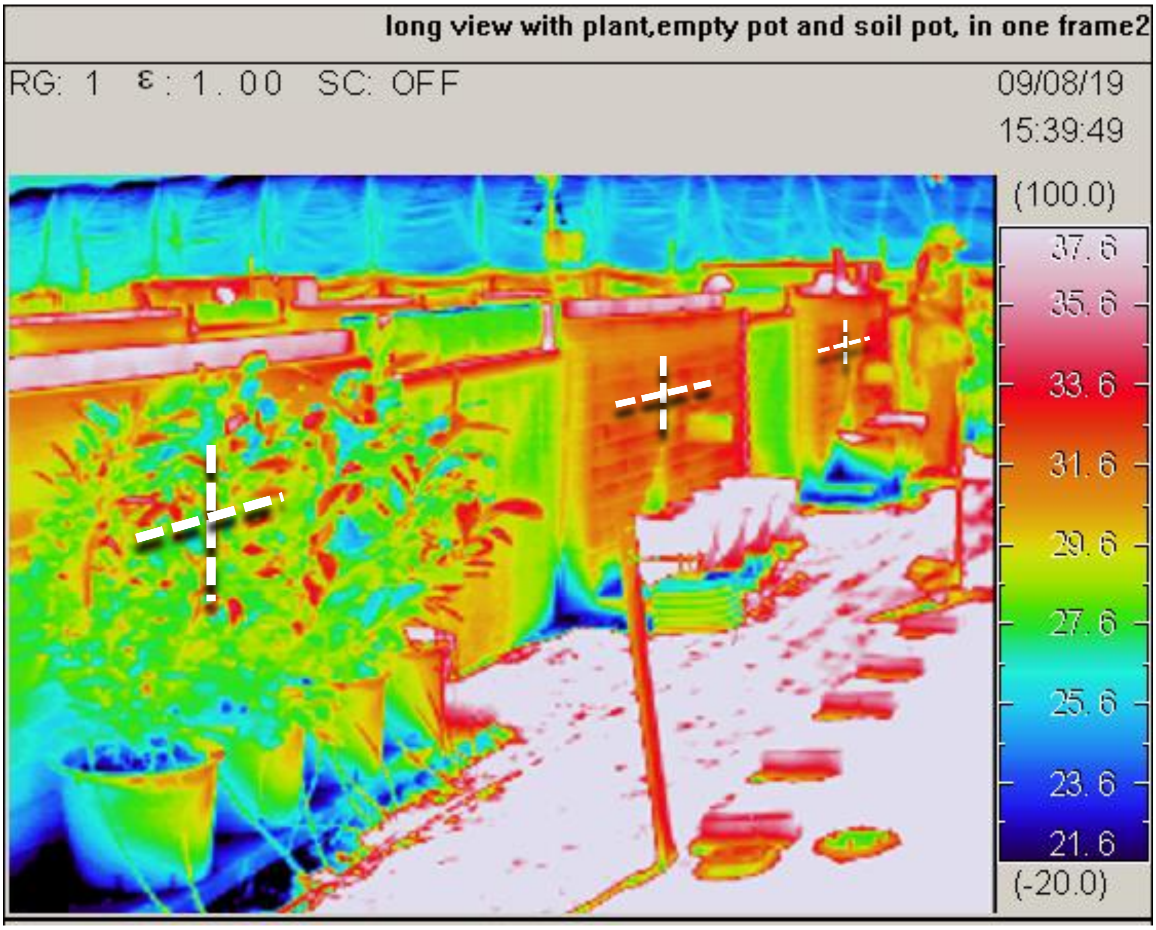

Figure 3. Mean hourly air temperature for walls flanked by *Prunus* (South = Δ; North = ▲), *Pot+media* (South = □; North = ■) or blank *Control* walls (South = ○; North = ●). Data restricted to days with ≥ 5 h irradiance > 120 W m^{-2}, August to September 2009. Bars = LSD (*P* = 0.05) blocked by date. Residual d.f. = 30 each time. Ambient temperature – dashed line.

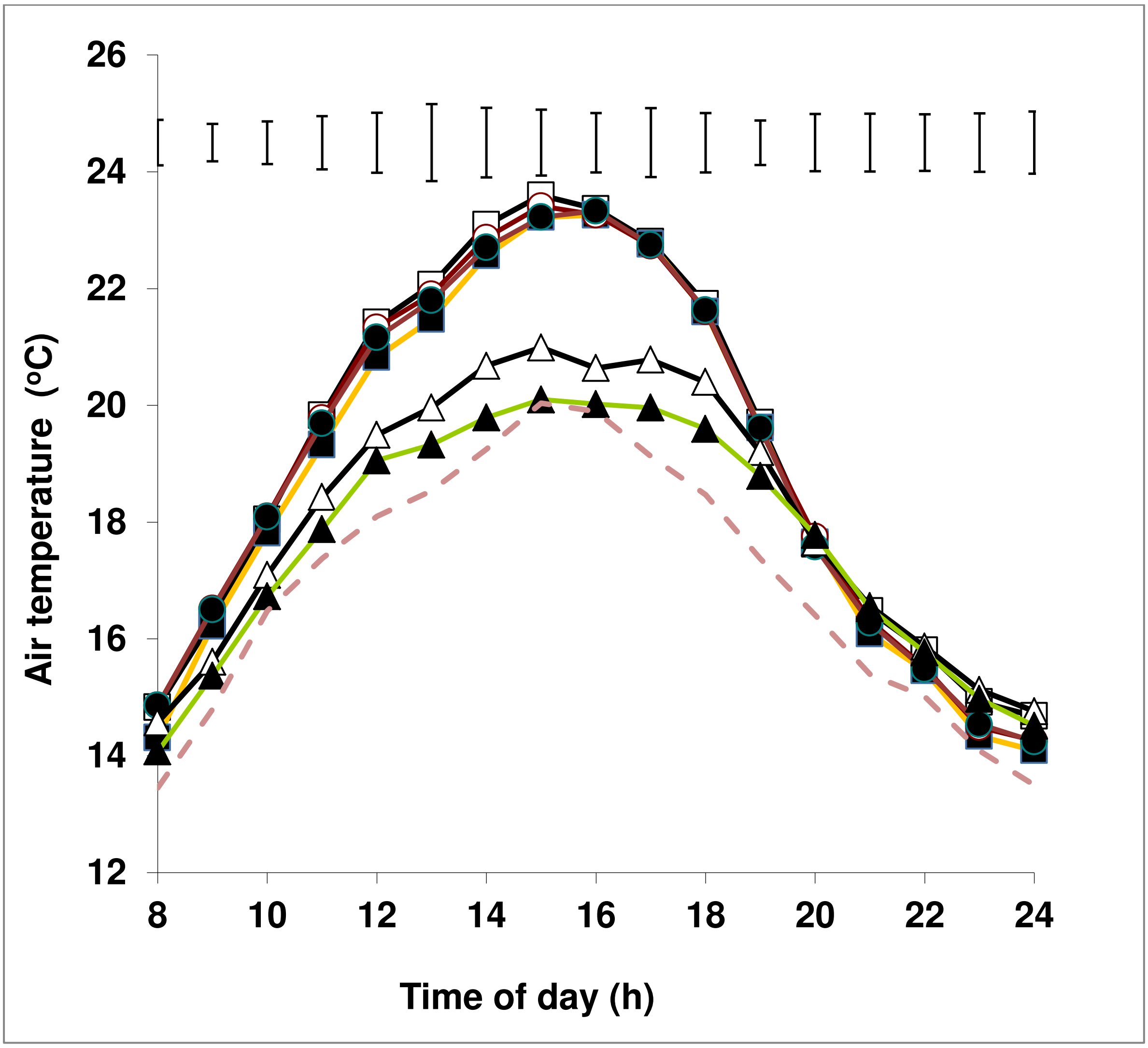

Figure 4. Mean hourly air temperature for walls flanked by *Prunus* (South = Δ; North = ▲), *Pot+media* (South = □; North = ■) or *Excised* (*Prunus)* stems (South = ○; North = ●). Data restricted to days with ≥ 5 h irradiance > 120 Wm^2 during mid-late September 2009. Bars = LSD (P = 0.05) blocked by date. Residual d.f. = 30 each time. Ambient temperature – dashed line.

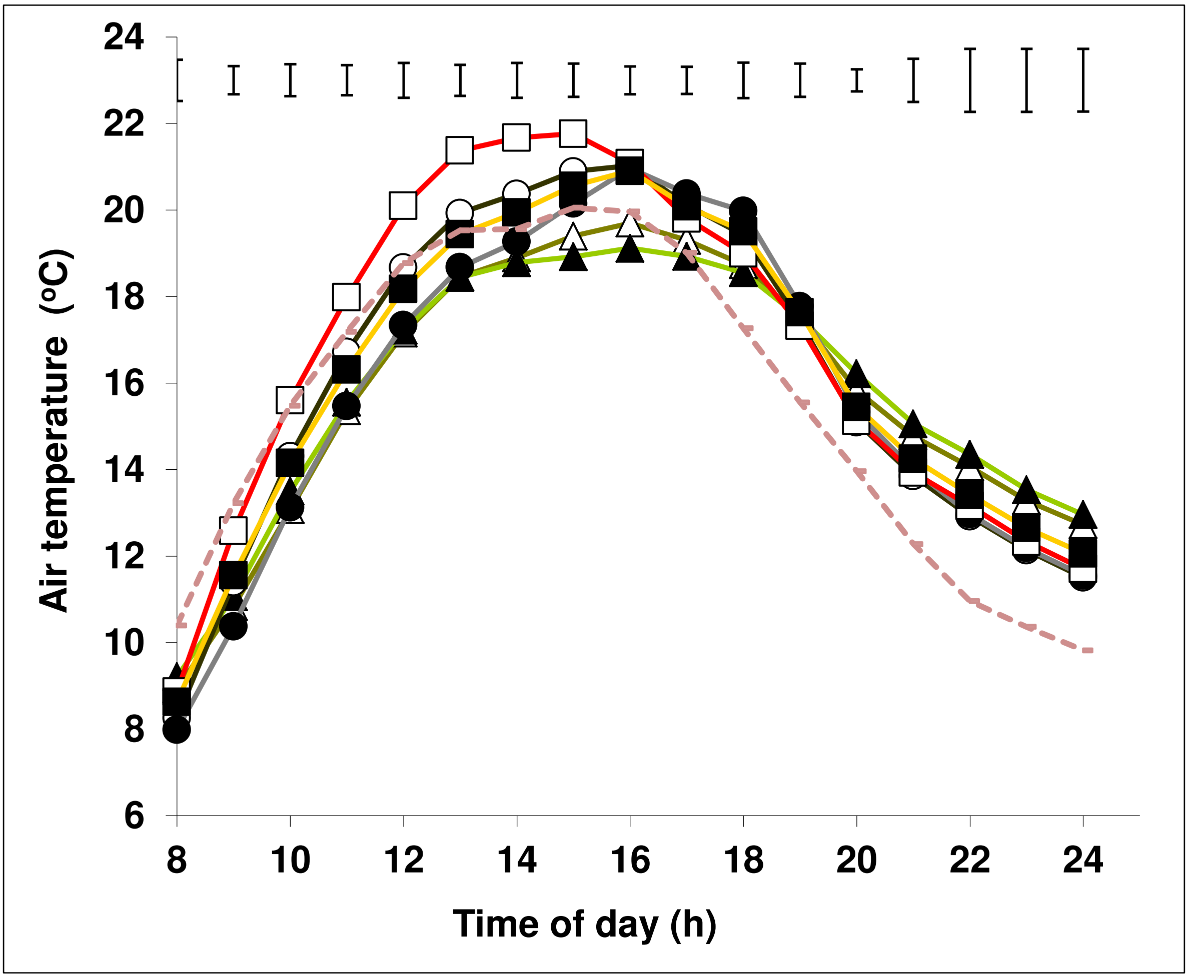

Figure 5. Reduction in wall temperature (^oC) attributed to planted troughs Tp with derived values for shade (Tp_{sh}), evapo-transpiration (Tp_{et}) and evaporation from medium (Tm). Bars = LSD (*P* = 0.05), d.f. = 32, for aforementioned parameters in order from left to right.

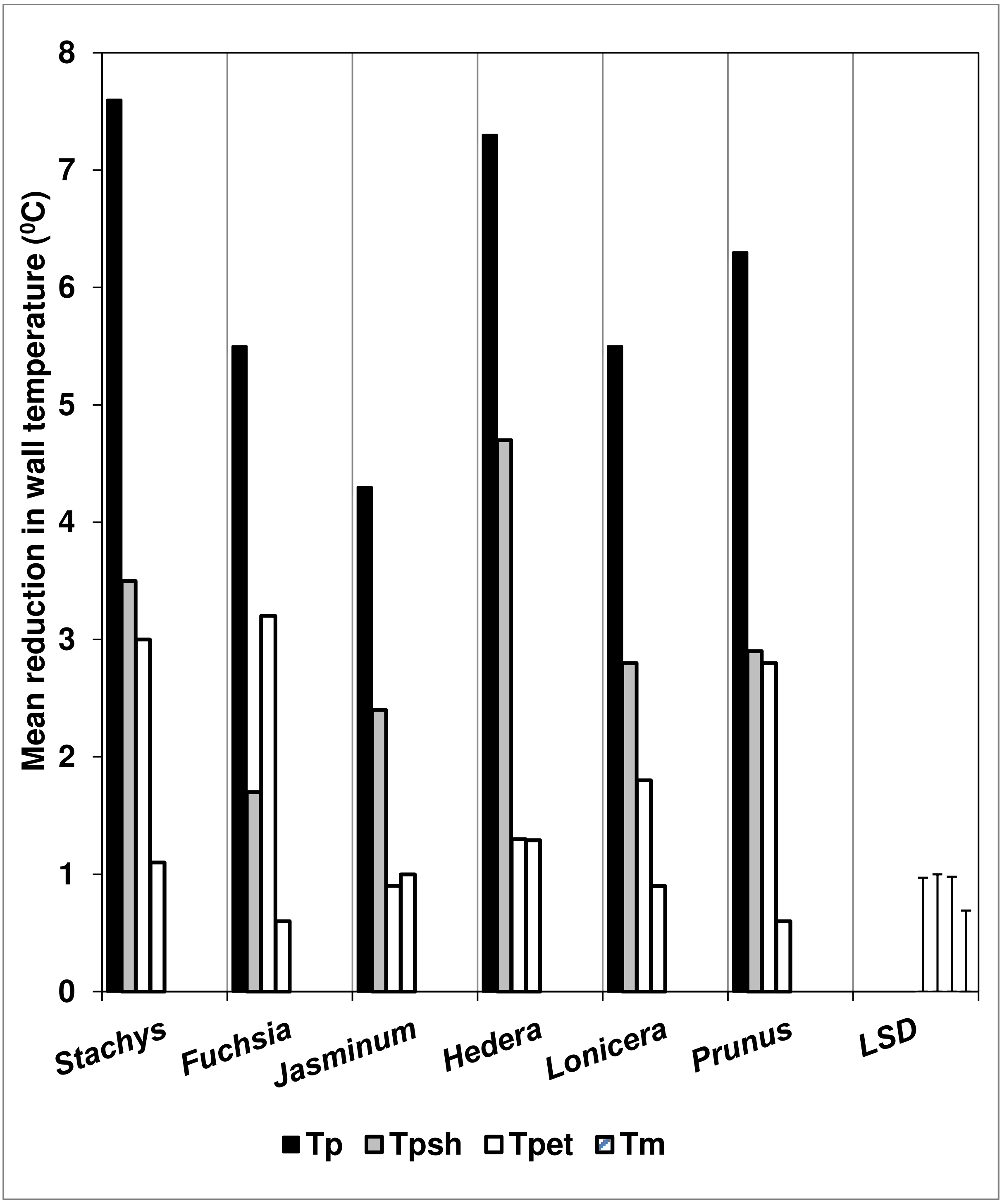

Figure 6. Mean Wall Leaf Area Index (WLAI) per trough. Bars = LSD (*P* = 0.05), d.f. = 17.

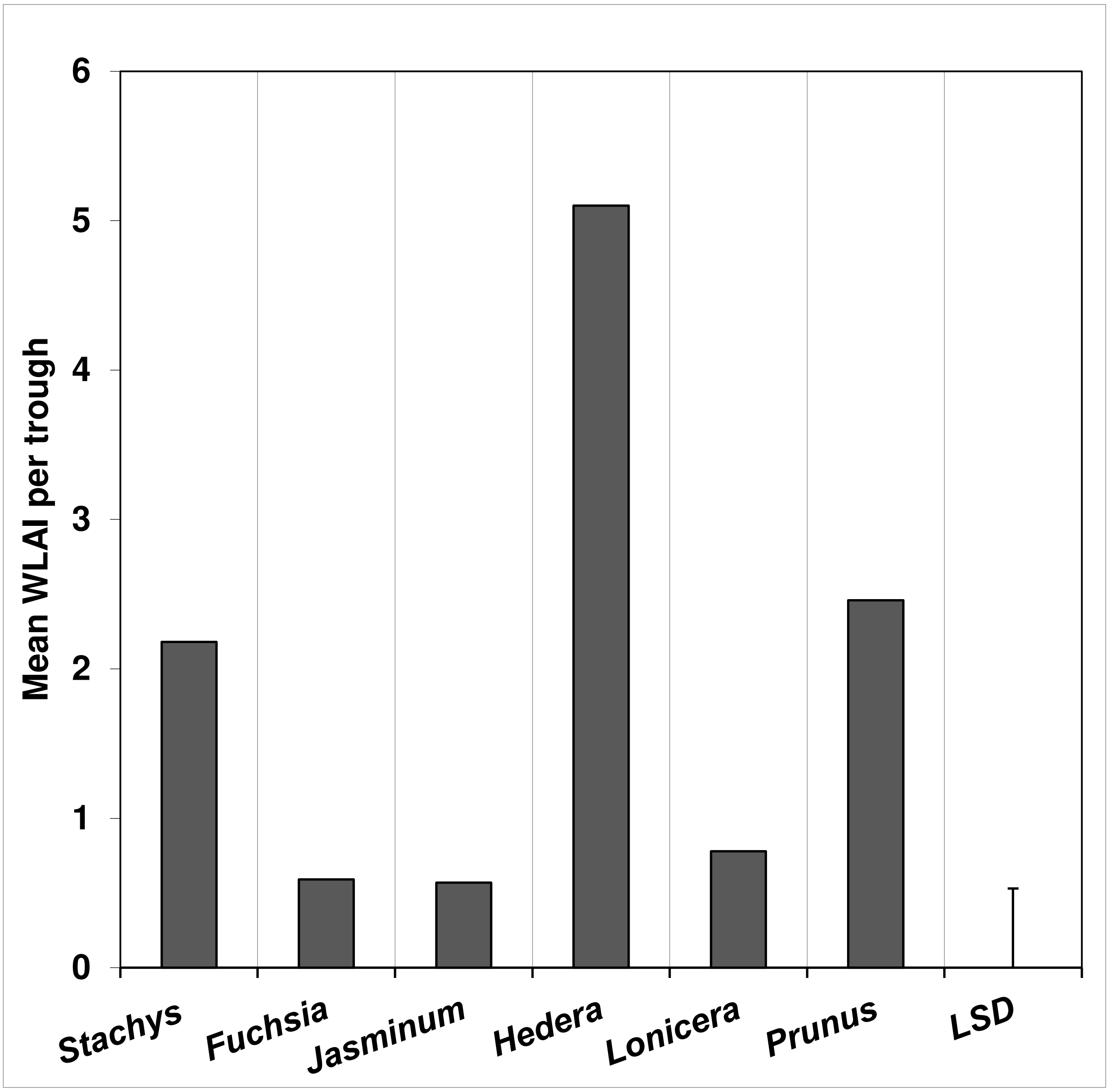

Figure 7: Comparison of mean cooling (°C) per unit of Wall Leaf Area Index (WLAI) for planted trough Tp, and derived values for shade (Tp_{sh}), and evapo-transpiration (Tp_{et}). Evaporation from medium (Tm). Bars = LSD (*P* = 0.05) respectively; d.f. = 32, for aforementioned parameters in order from left to right.