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Living wall influence on microclimates: an indoor case study

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Abstract. To address the call for developing passive climate resilience strategies, the project examines the influence and effectiveness of utilising vertical greening for reducing space-conditioning loads of urban buildings and surrounding microclimates. By examining this focus, the project aims to improve the design of urban built environments that would in turn lead to health and wellbeing enhancements of their growing populations. The purpose of this paper is to present preliminary findings from a monitoring campaign carried out at an indoor atrium case study in Cambridge, UK. Key parameters monitored included soil, surface, and air temperature; relative humidity; and surface air movement. Results obtained show relatively lower air temperature and higher relative humidity levels proximate to the living wall. Wintertime monitoring has also indicated a surface flow pattern that demonstrates the presence of a modest downdraught effect. Although these modifications are modest in magnitude, they could still offer significant localised thermal comfort benefit to building occupants, as well as potential for contributing to a reduced space-conditioning load.

1. Introduction

Passive green infrastructure enhancements are widely advocated to address urban climate risks such as increasing temperatures. In cities with dense morphologies, surface greening has received increased attention as means to resourcefully achieve such enhancements [1,2]. Although initial efforts promoted horizontal greening, vertical greening has gained significant favour owing to recent application advancements presenting greater opportunity to utilise the largest exposed area of the urban surface. Industry specialists and suppliers as a result report an upward trend in commissions received, while the body of research considering their various ecosystem benefits is similarly expanding [3].

Vertical greening describes any vertical built surface that is intentionally covered with plant life. The two principal approaches of 'green facades' and 'living walls' are differentiated based on the placing of the growth substrate [3]. While green facades are a well-established form of vertical greening, recent interest is directed at the latter living wall category [3]. These include the growth substrate placed on the vertical host building wall, where plants root into a substrate carrying support-work that includes embedded closed-loop irrigation and fertigation networks [4]. The greater prominence gained by living walls is mainly influenced by their flourishing aesthetic appeal, which has encouraged certain urban communities to assign greater value to such approaches [5]. Encouraged by this enthusiasm and demand, recent installations have been introduced to a diverse range of urban building typologies and scales, as well as outdoor and indoor conditions [3,6]. This paper is concerned with such living wall applications, with an indoor case study examined to quantify the microclimatic modifications introduced by its presence and sustained performance.

2. Methodology

The broader project had identified three urban morphological typologies to assess microclimatic modifications of living wall interventions; namely, outdoor street canyons, outdoor courts, and indoor atriums. This paper presents the results gathered from a monitoring campaign carried out at an indoor atrium condition.
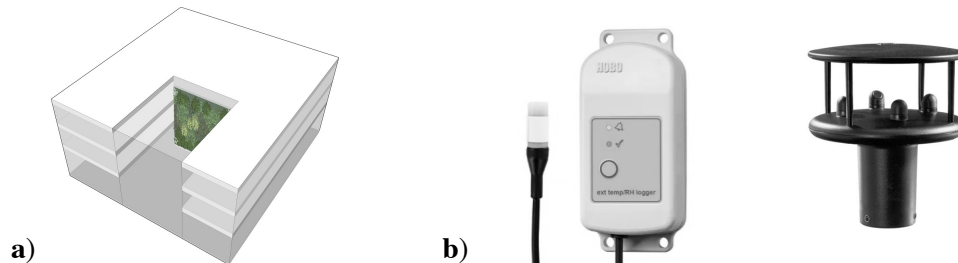

a)   b)

Figure 1. *Diagrammatic representation of a large installation within an indoor atrium (**a**); and instrumentation used for monitoring, including HOBO temperature and humidity logger, and WindSonic wind sensor (**b**).*

Within larger urban buildings, the general arrangement plan often includes a large atrium situated off the main entrance (see Figure 1a). This creates a transitional space, where a degree of relatability is maintained between the functions within the building and the outdoor environment. An example of such an atrium is presented at the David Attenborough Building in Cambridge. In this building, the northeast and southwest facing surfaces bounding the atrium are either building façades or internal partitions, while the southeast surface is host to a circulation core, and the remaining northwest surface is host to a three-storey living wall (Figure 2). The atrium top is bound by a southeast sloping skylight that floods the space with daylight, while the volume is naturally ventilated with only four entrance heaters to condition the space in winter.
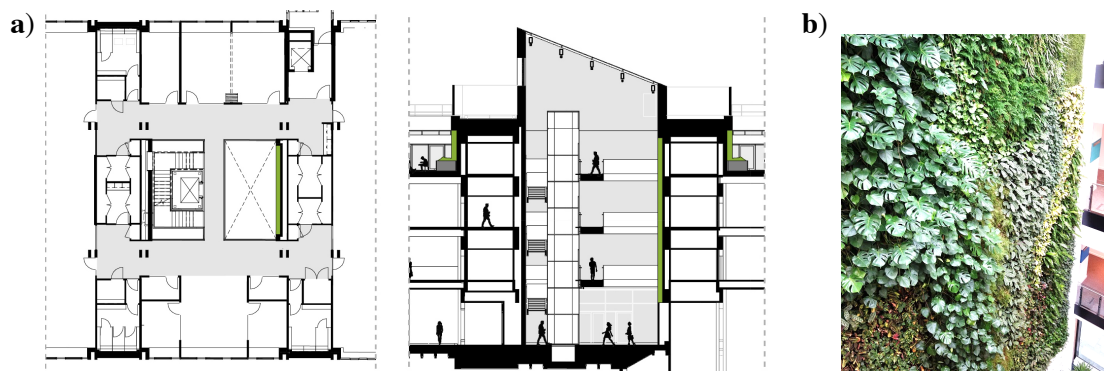

a)   b)

Figure 2. *Extracts from the Attenborough Building plan and section showing the atrium space (**a**); and the flourishing living wall in its current state (**b**).*

The 13 m-high, 91 m² living wall includes ~8,750 evergreen plants from 24 species representing eleven global regions and countries. Most species are in good health, although *Maranta leuconeura* plants had suffered from a combination of local heat stress from the entrance heaters, shading effect from neighbouring plants, and a spider mite infestation. These were replaced in spring 2019.

The monitoring of this case study included the measurement of soil, surface, and air temperature, relative humidity, and air movement off the surface to characterise the atrium's microclimate (see Figure 1b and Table 1). The hygrothermal observations were recorded between June 2018 to March 2019, with the period between June to September 2018 considered as summer, and between October 2018 to March 2019 considered as winter (heating period). The air movement monitoring was carried out between October to December 2018, to present wintertime readings.

Table 1. *Probe and logger deployment at the David Attenborough Building.*

Parameter measured	Placing within atrium	Logger and probe
Temperature and relative humidity	Suspended at each level (×03), 50 mm off the living wall surface and at 1.1 m AFFL	HOBO MX2302 temp. and relative humidity logger with external probe
Temperature and relative humidity	Suspended at level 2, 1.2 m off the living wall surface and at 1.1 m AFFL	As above
Ambient temperature and relative humidity	Within atrium, 6 m off the living wall surface and at 1.1 m AFFL	HOBO MX2301 temp. and relative humidity logger with internal probe
Surface temperature	Atrium northwest surface without living wall, at level 0 (base) and level 2 (approx. centre point of atrium)	HOBO U12-008 logger with external surface TMC6-HE temp. probe
Soil temperature	Atrium living wall at level 2, embedded in soil substrate	HOBO U12-008 logger with external TMC6-HD temp. probe
Air velocity and direction	Mounted perpendicular to the atrium living wall surface at its base on level 0 at 5 m AFFL	Gill WindSonic 1 air velocity and direction sensor

3. Findings

The results presented here refer firstly to surface hygrothermal influences, and secondly to surface air movement observations.
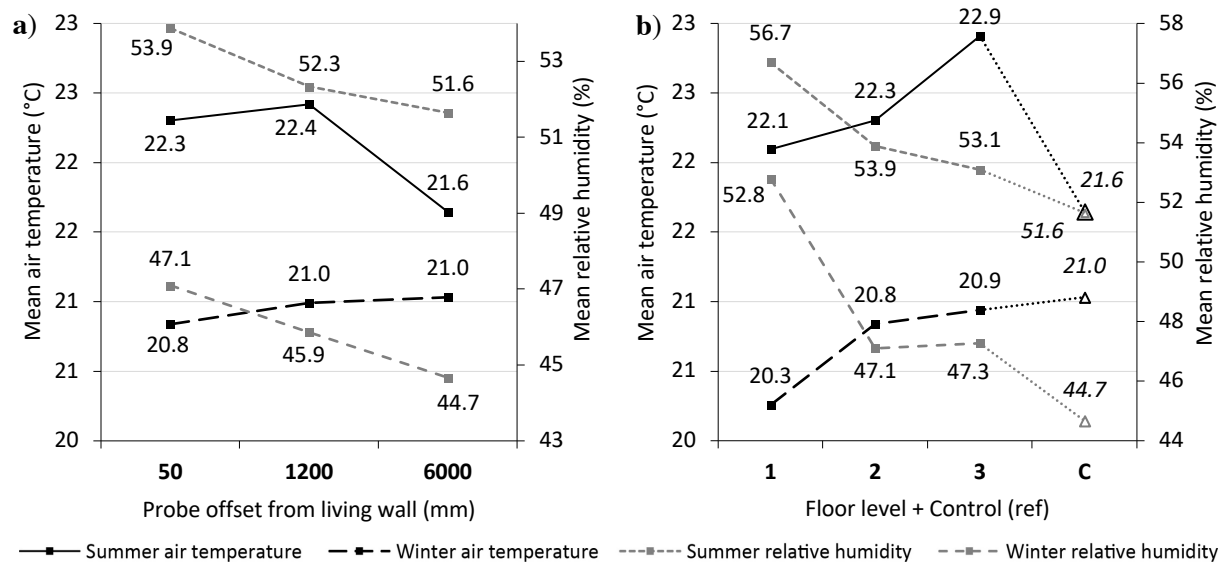

Figure 3. *Horizontal (**a**) and vertical (**b**) mean air temperature (°C) and relative humidity (%) distribution.*
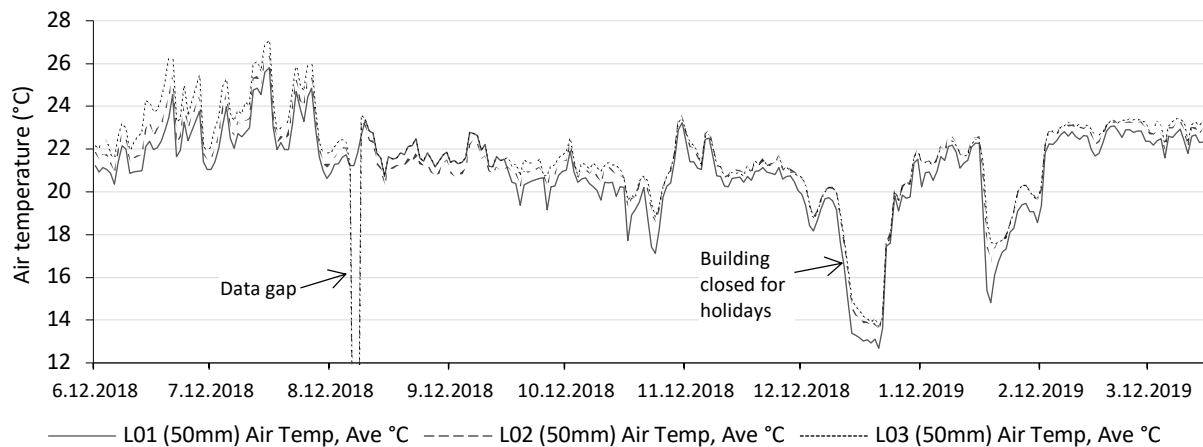

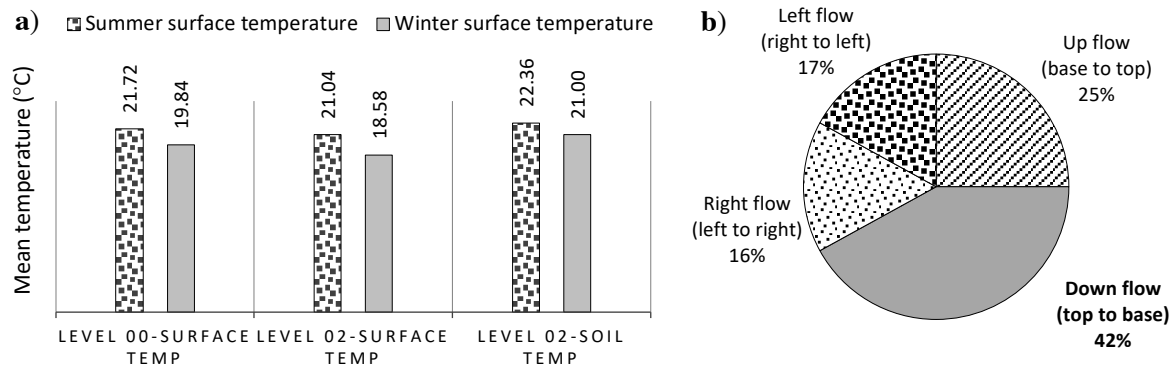***Figure 4.*** *Air temperature (°C) vertical profiles from levels one-to-three, from summer-to-winter.*

Figure 5. *Mean surface and soil temperatures (°C) (**a**); and surface air movement distribution (%) by quadrant (**b**).*

4. Discussion

4.1 Indoor air temperature

Preceding studies have demonstrated the addition of vertical greening to the exterior building envelope to increase its thermal buffering properties, which in turn could improve indoor comfort and reduce summer cooling loads [7,8]. The investigation of such thermal effects when vertical greening is applied within an indoor environment however is scarce at present. An exception was presented by a laboratory-based study by Pérez-Urrestarazu *et al*. [9] of an active living wall (ALW), where they found its cooling efficiency to be at its best when room conditions were drier and warmer. This improved performance when conditions are at their harshest generally agrees with studies of exterior conditions [3]. They emphasised that although the cooling extent gained by this interior application was relatively modest, the benefit could still contribute to potential energy savings by reducing cooling loads [9].

In this case study, the mean temperature distribution profile across the atrium varied between summer and winter. In winter, the profile agreed with Pérez-Urrestarazu *et al*. [9] observations to present linear increasing means across the atrium with the lowest or coolest temperature recorded proximate to the living wall surface (0.2 % relative temperature decrease between 6000 to 1200 mm, and 0.7 % between 1200 to 50 mm). In summer, the lowest mean was at the 6000 mm probe, while a relative 3.6 % increase from this mean was recorded at 1200 mm, followed by a 0.5 % decrease proximate (50 mm) to the living wall surface (see Figure 3a). The latter summer observation suggests that interference from another source affects the horizontal temperature distribution profile. Considering the three levels, stratification of temperature and relative humidity means is evident and particularly pronounced in the summer, with temperatures increasing and relative humidity decreasing with floor level (Figure 3b & Figure 4). This suggests the possible presence of a buoyancy driven stack flow in the atrium volume, which would explain the summertime disruption in the horizontal temperature distribution gradient mentioned earlier.

With surface temperature (see Figure 5a), a modest decrease in means was noted between level 0 (proximate to the base of the living wall) and level 2 (proximate to the vertical mid-point); 3 % in summer and 6 % in winter. This suggests that surface temperature influence on contextual surfaces increases when proximate to the central or core parts of the living wall, which was pronounced in winter as the ambient temperatures were lower while the evergreen wall sustained its growth and ecosystem service provision. The level 2 soil temperature mean was notably higher than the monitored corresponding surface temperature (6 % in summer and 13 % in winter), and proximate air temperature (0.3 % in summer and 0.8 % in winter), which could be attributed to its heat storage properties, as well as heat generated from sustained rhizosphere microbiome activity.

4.2 Moisture influence

Vertical greening is identified to contribute a bio-protective moderating moisture influence, which is characterised in studies with relative humidity measurements mainly taken relative to a control condition, and to a much lesser extent with increasing distance from the host wall to assess effective range of influence. An experimental approach by Susorova *et al*. [10] for example, found relative

humidity to be highest inside vegetation layers, although absolute humidity was unaffected. The latter suggests that relative humidity is increased by the cooling of the foliage air temperature, while the humidity produced by transpiration may be utilised to maintain good foliage health during warmer summertime conditions. The self-generating humid microclimate therefore assists in sustaining good plant health [4], with multi-layered foliage canopies better able to sustain and regulate such self-hydrating canopy conditions [11].

Beyond the foliage canopy zone however, the influence range of this humid microclimate is said to be limited. For example, the *Mur Vegetal* designer Patrick Blanc [4] had reported relative humidity to decay from 90 % at 50 mm; 80 % at 100-200 mm; 70 % at 300-500 mm; 60-65 % at 1 m; and normalise at 59 % ambient humidity around 1.5 m away from the hydroculture felt of the living wall system. With this monitoring study, mean relative humidity was recorded at its greatest proximate to the living wall canopy (see Figure 3a), while the horizontal distribution decayed from 90 % at 50 mm to 28 % in summer and 44 % in winter at the 1200 mm probe (6000 mm probe representing ambient relative humidity).

More data however is needed to quantify indoor humidity influence, as increasing levels is a risk to both building occupant health and thermal comfort. Historical studies examining indoor conditions had demonstrated humidity to increase with the addition of potted houseplants, although at substantially less capacity than amounts generated by other industrial devices to cause harm to health and comfort [12,13]. As much greater plant cover is introduced by living walls than potted plants, the study of indoor humidity effects of such features is emphasised as requiring further attention.

4.3 Surface air flow modification

The cooling provided by evapotranspiration, together with the differential shade cooling and solar gain heating of foliage encourages the formation of a surface proximate dynamic thermal mixing zone [14]. The relatively cooler surface presented by vegetation could also generate cold radiation effects, and the potential formation of a 'downdraught effect' resulting from natural convective boundary layer flows along the surface. Such cold surface effects are well-documented in indoor environments, with studies mainly examining cold window surfaces [15]. The occurrence of such effects cause occupant discomfort, with draughts identified to be more critical than reduced operative temperatures or radiation asymmetry [16]. An experimental study by Heiselberg [15] found discomfort determined by the percentage of dissatisfied persons to rapidly decrease within the first 2 m off the surface owing to the reduction in maximum velocity, which highlights the strong proximity influence of such effects.

Minimal evidence is presented in current research to confirm the occurrence of such effects relative to vertical greening applications. In exterior conditions such effects are likely to be noticeable only under extremely stable conditions with negligible wind velocities. At higher velocities, turbulent mixing could rapidly normalise such micro-scale effects, which explains why some studies have failed to record any air temperature influence in zones fronting facades [e.g. 17]. With indoor conditions however, there is greater potential for such convective boundary layer flows and cold radiation effects to develop, which in turn could either threaten or benefit occupant thermal comfort. In this study, surface air movement monitoring results revealed that during the winter period, a dominant downdraught was recorded (see Figure 5b), with 42 % of the directional readings reported for the quadrant (>135° and <225°; mean velocity 0.128 m s^{-1}, SD 0.077). Notwithstanding this observation, there is no evidence at present to suggest that this effect is entirely driven by the presence of the living wall. Further simulations are therefore necessary to determine the key influences affecting this observation.

5. Conclusion

Previous studies assessing thermal influence had presented evidence to suggest that exterior vertical greening belonging to both categories offer significant benefit, with cooling influence in the summer. The variance in thermal performance observed with the two categories and their variant systems had been explained by factors including build-up and presence of an intermediate cavity, substrate properties, irrigation, vegetation coverage characteristics, and the interaction of such factors with the

background climate. There is some evidence to suggest better performance in drier, warmer climates, with more evidence required for temperate climates. Considering this available body of work, there is clear bias toward assessing exterior applications as opposed to interior installations. Addressing this shortfall is a key aim of this project, the initial findings of which have been discussed here.

When considering the initial data gathered from the indoor case study monitored, a surface proximate cooling influence was recorded at all three levels relative to the control condition for the atrium volume. This cooling influence was however contrasted by a surface proximate humidifying effect. The atrium volume including the living wall presents a stratified hygrothermal microclimate that is more pronounced in the summer than in winter; the buoyancy driven flow from which could be disrupting the distribution of hygrothermal influence generated by the living wall. Preliminary analysis of air movement and velocity data gathered off the surface over the autumn-to-winter months suggests that a dominant downward flow exists. However, whether this is entirely the result of a downdraught effect influenced by the living wall is uncertain. The next stage of the project would therefore seek to better understand the atrium's airflow drivers by utilising a simulation model.

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