PLEA 2020 A CORUÑA
Planning Post Carbon Cities

Characterising living wall microclimate modifications in sheltered urban conditions

findings from two monitored case studies

KANCHANE GUNAWARDENA,[1] KOEN STEEMERS,[1]

[1]The Martin Centre for Architectural and Urban Studies,
Department of Architecture, University of Cambridge, 1-5 Scroope Terrace, Cambridge, CB2 1PX, UK

ABSTRACT: Green infrastructure enhancements are widely advocated to address heat-related risks in cities. The challenge of implementing enhancements in dense cities has necessitated the development of surface greening, with living walls having gained increased prominence in recent years. This paper considered such in-situ applications to quantify the extents of their influence on the microclimates of two sheltered urban conditions. The results highlight the potency of hygrothermal modifications to be most apparent within the immediate zone, while the disparity in influence between the two studies suggest that with increased shelter the hygrothermal influence is likely to be relatively weaker. Surface temperature monitoring results from the Indoor case study presented significant variation. While these were not potent enough to cause radiation asymmetry associated discomfort, thermal sensation and diversity to occupants is probable. These findings therefore highlight the necessity for designers to take account of this proximity influence, and in future designs to increase building occupant access to installations.

KEYWORDS: Urban greening, vertical greening, living walls, living wall monitoring, microclimate modification

1. INTRODUCTION

To address the call for developing passive climate resilience strategies, the project investigates the influence and effectiveness of utilising vertical greening for reducing energy loads of urban buildings and surrounding microclimates. By examining this green infrastructure focus, the project aims to improve urban built environments that would in turn lead to health and wellbeing enhancements of their ever-growing populations.

Although vertical greening includes the two principal approaches of ‘green facades’ and ‘living walls’, recent interest is directed at the latter [1–2]. The plants in such systems root into a substrate (natural or synthetic porous/fibrous media) carrying support-work that includes irrigation and fertigation supply. The greater prominence of living walls is attributed to their flourishing aesthetic appeal, with recent installations introduced to various building typologies, scales, and outdoor, semi-outdoor, and indoor conditions [2–4].

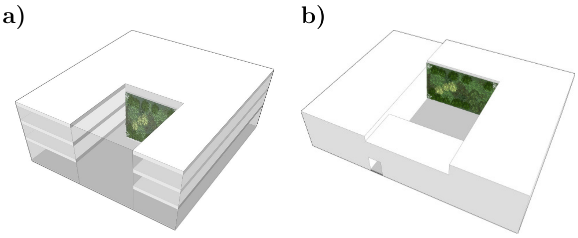

Figure 1.Diagrammatic representation of an installation in an indoor atrium (a); and a semi-outdoor courtyard (b).

The purpose of this conference paper is to present findings from monitoring campaigns carried out at two sheltered living wall (indoor and semi-outdoor) case studies that characterises their microclimate modifications (Figure 1). Key parameters monitored included soil, surface, and air temperature, as well as relative humidity.

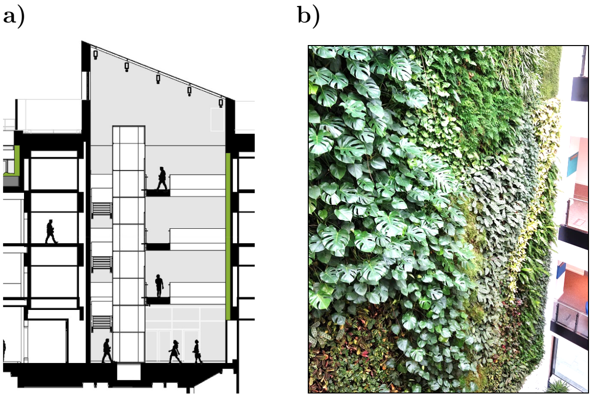

Figure 2. Extract from the building section showing the atrium (a); and the living wall in its current state (b).

1.1 Indoor atrium

Within urban buildings the general arrangement often includes a large atrium situated off the entrance. An example of such an atrium is located at a campus building in Cambridge, England (Cfb Köppen climate), where the northwest atrium surface is host to a flourishing three-storey living wall (Figure 2).

This installation is 13 m-high and 91 m^2 in coverage, with ~8,750 evergreen plants from 24 species planted onto a soil-based, modular interlocking crate system [5].

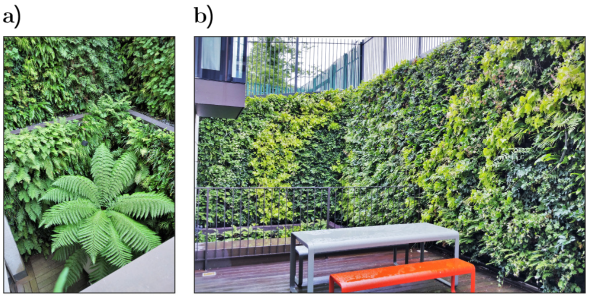

Figure 3. Residential courtyard in Primrose Hill, London, basement level court (a); east- and south-facing walls of the terrace court (b).

1.2 Semi-outdoor courtyard

The monitored courtyard is in Primrose Hill, London (Cfb) and has living walls installed on three bounding surfaces of the sheltered court, while the remaining north face is represented by the stone and glazed façade of the residential building. The arrangement includes a lower level which continues the living walls at the northwest corner down to form a basement court (Figure 3). The living walls have an average height of ~4 m and a total area of ~102 m^2; with ~5,000 plants representing 14 species planted onto a soil-based, modular felt-pocket system [5].

2. METHODOLOGY

The monitoring of the indoor atrium case study in Cambridge included the measurement of soil (SoilT), surface (ST), and air temperatures (AT), and relative humidity (RH); while absolute humidity (AH) was calculated. 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.

The monitoring of the semi-outdoor case study in Primrose Hill included the measurement of AT and RH, with absolute humidity (AH) calculated to characterise the courtyard's microclimate. The hygrothermal observations were recorded between August 2018 to December 2019, with the period between May-to-September considered as summer, and between October-to-April as winter.

The apparatus used for the exercises included manufacturer calibrated HOBO (Onset Computer Corporation, Bourne, MA, USA) and Tinytag (Gemini Data Loggers, Chichester, West Sussex, UK) AT, RH, and ST probes and loggers. All data was processed and analysed using Matlab R2019a (MathWorks, Natick, MA, USA) software. For large datasets (N >300), normality was determined with reference to skewness and kurtosis thresholds, with failures assessed with nonparametric tests. Given that mean value datasets and their relation to probe locating parameters were limited (N <5), the relationships were plotted as profiles for discussion (see Figure 4 and Figure 5).

3. FINDINGS

3.1 Hygrothermal profiles

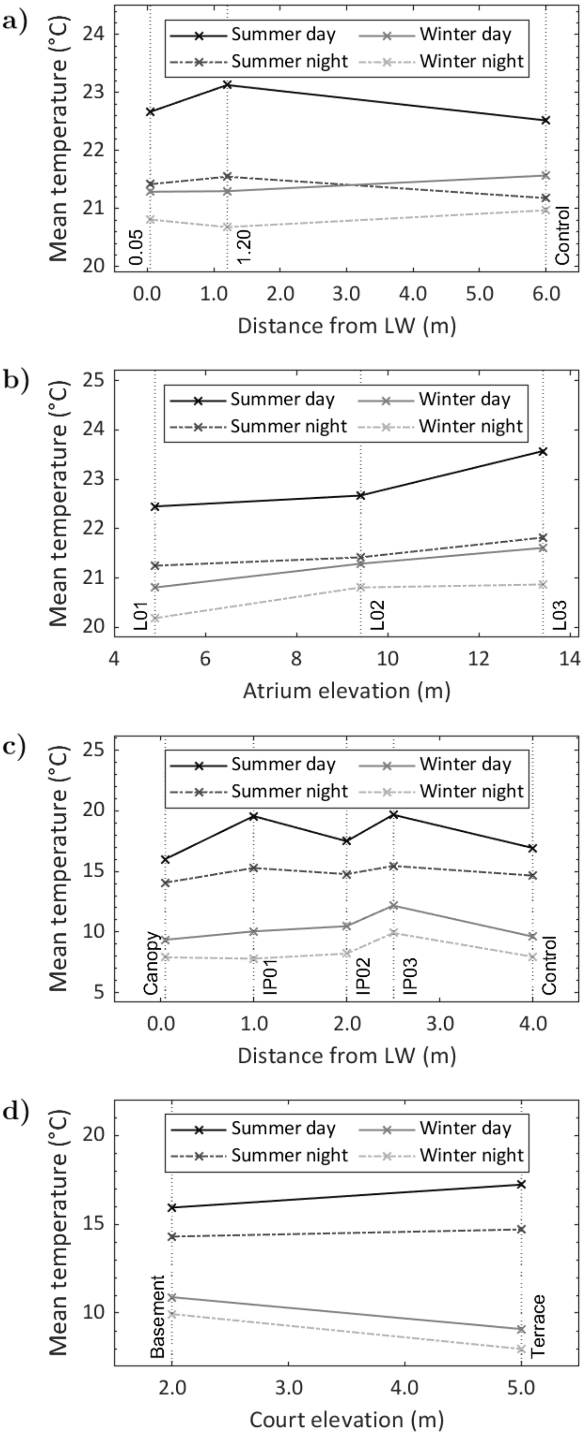

Figure 4. Mean AT profiles for indoor case study horizontal (a) and vertical (b) distribution; and semi-outdoor case study horizontal (c) and vertical (d) distribution.

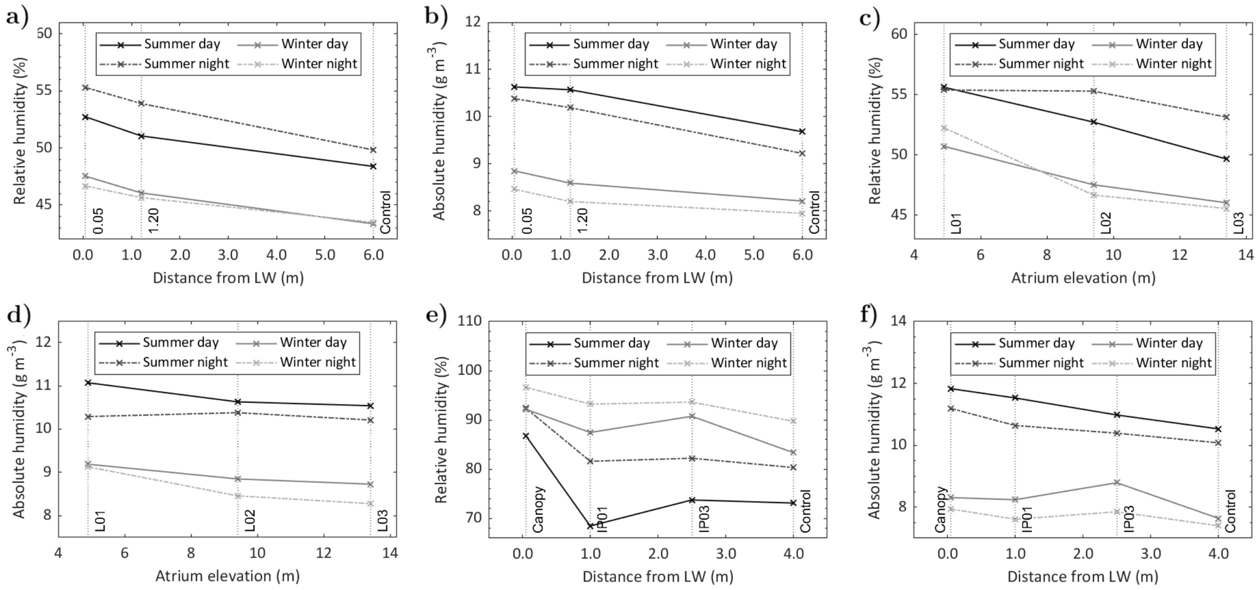

Figure 5. Mean RH and AH profiles for horizontal (a & b) and vertical (c & d) distribution at the indoor study; and for horizontal distribution at the semi-outdoor study (e & f).

3.2 Surface temperatures

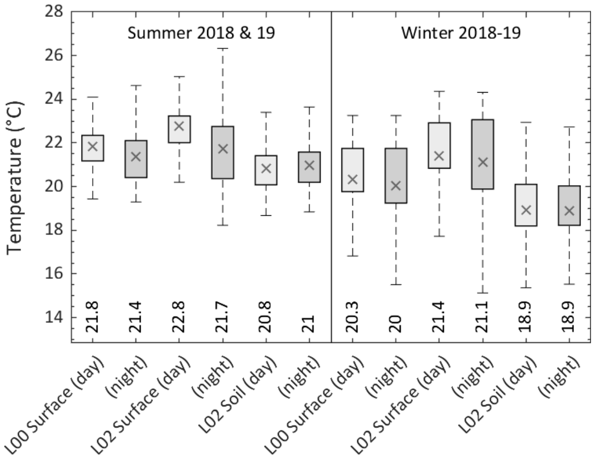

Figure 6. Atrium ST and SoilT datasets, with means ('x').

Table 1. Atrium ST and SoilT influence.

Temp. (°C)	SUMMER 2018 & 19 ST (L00 - L02)	L02 (ST - SoilT)	WINTER 2018-19 ST (L00 - L02)	L02 (ST - SoilT)
Daytime	-0.93 (±0.01), -4.2%	1.95 (±0.01), 8.6%	-1.09 (±0.02), -5.4%	2.48 (±0.02), 11.6%
{L00 ST}	{L02: 104.2%}		{L02: 105.4%}	
{L02 ST}		{L02 SoilT: 91.4%}		{L02 SoilT: 88.4%}
{L02 AT}		{L02 SoilT: 91.9%}		{L02 SoilT: 88.9%}
Night-time	-0.38 (±0.01), -1.8%	0.76 (±0.01), 3.5%	-1.08 (±0.02), -5.4%	2.23 (±0.02), 10.6%
{L00 ST}	{L02: 101.8%}		{L02: 105.4%}	
{L02 ST}		{L02 SoilT: 96.5%}		{L02 SoilT: 89.4%}
{L02 AT}		{L02 SoilT: 97.9%}		{L02 SoilT: 90.7%}

Note: '{ }' refer to values relative to L00 ST; L02 ST; L02 AT: 100%.

4. DISCUSSION

4.1 Air temperature influence

With the indoor case study, the Control demonstrated weak correlations and shared variance (r^2) with the outdoor climate. Mean ambient (Control) ATs still varied seasonally, with summer M = 0.95, ±0.014 K during the daytime and M = 0.21, ±0.015 K during the night-time warmer than winter. This modest variation is expected given that the atrium is mostly naturally ventilated. Control reading relationships with atrium probes on the other hand were very strong, and strongest with horizontal than vertical distribution probes. The weakest of these relationships were however during the summer daytime, which suggested interference from another source. Owing to this disruption, living wall horizontal AT distribution influence is best limited to the discussion between the 0.05 and 1.20 m probes, where the latter datasets showed >99% AT variability with the 0.05 m dataset. When mean AT profiles were examined (Figure 4a), the summer day and night-time, and winter daytime profiles agreed with Pérez-Urrestarazu *et al.* (2016) observations to present increased means at the 1.20 m probe (2.0, 0.1, and 0.05% respectively). Thus save for the winter night-time profile, all others presented cooler ATs immediate to the living wall (M ~0.5 K coolest AT difference during summer daytime), in agreement with previous vertical greening studies [1–7–8].

Vertical AT profiles showed the presence of a thermal gradient with means increasing with atrium floor levels L01-to-L03 (Figure 4b). L03 as a result presented the warmest canopy proximate ATs, with the summer presenting the highest means. The gradient confirms the presence of a buoyancy-driven stack-effect, which had pronounced influence in the summer. This flow is also likely to be the principal contributor towards the summertime interference at the Control probe mentioned above. The dataset correlations showed that 63% of L02 and 38% of L03's AT variability to be explained by L01. The contributions from rising thermals from the lower level were therefore progressively supplemented by loading from intermediate floor level gains, as well as higher irradiance exposure from the installation upper region's proximity to the atrium rooflight.

With the semi-outdoor case study, the Control demonstrated strong correlations and r^2 (98.2%) with the outdoor climate. Control mean ATs as a result varied seasonally with summer M = 7.31, ±0.02 K during the daytime and M = 6.69, ±0.02 K during the night-time warmer than winter. The much greater mean difference relative to the indoor study is expected given the court's exposure to the elements, regardless of its sheltering boundaries. The Control readings however presented lower means for both day and night-time than intermediate horizontal distribution probes (Figure 4c). This suggested interference, which could be attributed to the influence of the building façade's thermal properties. The Control AT means however were still higher than the canopy probe, with the latter having presented the lowest means (coolest M = 0.9 K influence for summer daytime relative to Control). The lowest cooling influence was for the winter night-time (M = 0.05 K), which suggests significantly reduced cooling contribution from the evergreen cover. This is expected given that photosynthesis and transpiration is negligible during nocturnal hours, which is exacerbated by evergreen efficiencies being lower in winter [9–10]. Horizontal AT influence distribution was notably nonlinear in the summer, with the intermediate probes (IPs) presenting relatively higher means and a daytime drop at IP02 (Figure 4c). The reason for this daytime drop is unclear at present and could be due to mixing introduced from an unidentified source.

Given that only two vertical points were monitored at this study (~3 m elevational difference), a clear thermal disparity was evident with the Terrace presenting warmer day (1.29 K) and night-time (0.40 K) means relative to the Basement in summer, while in winter this was inverted (1.79 and 1.96 K respectively). This latter inverted profile (Figure 4d) contrasts with the indoor study, although is explained by the basement court's subterranean condition where it is subject to greater thermal conduction influences from its two retaining boundary walls (including living walls), and heat gains from adjoining basement living spaces. Daytime Terrace AT variance on the other hand highlighted the significance of irradiance loading variations.

4.2 Moisture influence

With the indoor case study, the recorded Control RH mean range between 43-55% is within the 40-60% range recommended for office environments [11], although is below the typical requirements (85-95%) to maintain evergreen foliage health [1–12]. The Control RH readings showed weak r^2 (~7%) with the outdoor climate, although seasonal variation was evident with summer M = 5.03, ±0.06% during the daytime and M = 6.35, ±0.06% during the night-time greater than winter; while AH presented summer M = 15.2% during the daytime and M = 13.8% during the night-time greater than winter. These variations are again expected given that the atrium is predominantly naturally ventilated. Notably, Control RH variation was explained mostly by AH (r^2 = 61%) variance than AT (17%).

The horizontal RH distribution from the living wall to the Control decreased in winter and summer, and both day and night-time, with steeper gradients between the 0.05 and 1.20 m probes (Figure 5a). The highest RH was therefore always proximate to the living wall canopy (M = 5.5% L02 increase relative to the Control in summer night-time), in agreement with previous vertical greening studies [7–13]. AH profiles complemented this trend, with the maximum summer night-time mean increase for L02 relative to the Control at 13%. The summer daytime difference between 0.05 and 1.20 m probes however was notably marginal (2.5%), which suggests that during this period living wall proximate RH increase was mostly affected by AT cooling than by an increase in humidity. This is in agreement with the Susorova *et al.* (2014) study, where a significant fraction of the humidity from transpiration was found to be utilised to maintain foliage health in warmer conditions.

RH means at the indoor study also presented a vertical gradient with means decreasing from floor levels L01-to-L03 (Figure 5c). L01 therefore presented the highest RH (M = 8.8% summer night-time), as well as AH (M = 14.5% summer night-time relative to the Control). The AH mean difference between L02 and L03 however was notably minimal (<1%); thereby highlighting the RH reductions at the upper levels to be dominantly influenced by the AT increase of the thermal gradient.

With the semi-outdoor study, the Control RH showed strong correlation (r^2 = 87%) with the outdoor climate (weaker than AT: 98.2%). Control mean RH as a result varied seasonally, with summer M = 10.23, ±0.09% during the daytime and M = 9.40, ±0.07% during the night-time lesser than winter; while AH presented summer M = 27.4% during the daytime and M = 26.6% during the night-time greater than winter. These larger variations in relation to the indoor study is again expected given the court's exposure. All RH means were as a result significantly higher (68-97%) than at the indoor atrium (43-56%), with wintertime means exceeding the upper limit for comfort (70%). AH means however highlighted that humidity was only ~9% greater than at the indoor atrium over the summer, while in winter it was ~7% lesser. RH variation was therefore explained mostly by AT (r^2 = 18%) variance than AH (1.4%).

In agreement with the indoor atrium, the highest RH means for all conditions was at the Canopy probe (summer daytime M = 13.7%, highest relative to Control). The horizontal distribution showed RH reduction to be greatest (M = 18.4% for summer daytime) between the Canopy and IP01 probe, while at IP02, RH showed a relative increase (pronounced for summer profiles, Figure 5e), similar to the mean AT drop discussed earlier. For the summer profiles, examining AH means highlighted this RH increase to be influenced by the dip in AT. In winter however, IP02 demonstrated an increase in AH to disrupt the linear decay, as observed with summertime AH decay. This again highlighted interference from an unidentified source. Although AH decay in the summer was significant, it still showed substantial influence within the most frequented zone of the 4 m deep court. This is aided by the court's sheltered boundary conditions, where limited exposure to ambient airflow reduces opportunity for humidity advection. Summertime discomfort risk however is still to be reported by the residential occupants.

4.3 Surface temperature influence

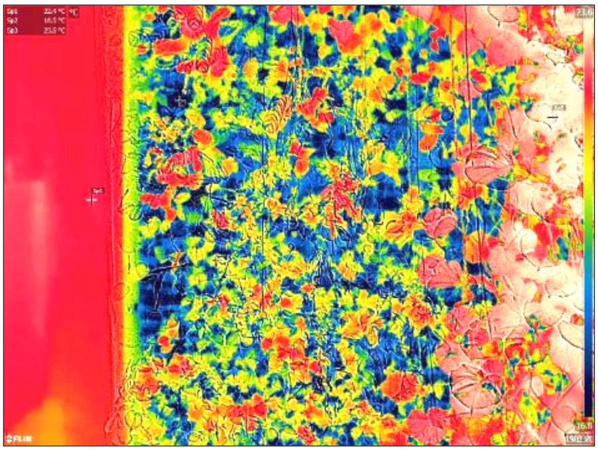

Figure 7. Thermogram of indoor study wall showing cooler (blue) substrate areas (5.9 K cooler than bare wall to left).

With indoor case study STs, an increase in means was recorded between L00 (base of the living wall) and L02 (vertical mid-point), both day and night-time, and in summer and winter (Figure 6 and Table 1). The relatively weaker correlations presented between the two floor levels in the summer suggests greater thermal contribution from another source to affect the ST increase. This could be partly attributed to the midsection of the installation wall receiving greater summertime irradiance penetration from the rooflight above, relative to the L00 base condition. The relatively stronger correlations presented with wintertime data (which also presented higher mean STs) on the other hand suggests greater contribution from the AT thermal gradient within the atrium volume; which is further clarified by the marginally stronger correlations (r_s >0.97) between L02 ATs and corresponding STs.

The recorded L02 SoilT means were notably lower than the corresponding ST and AT, both day and night-time and in summer and winter (Figure 6 and Table 1). This could be attributed to the moisture retention properties (increase in heat capacity) and continued evaporation from exposed soil surfaces. Passive qualitative thermography of the installation confirmed the soil substrate to be the coolest surface within the atrium volume, with some ST differences as large as ~6 K (e.g. Figure 7). Significant ST differences between areas could result in radiation asymmetry associated discomfort. The maximum differences recorded however were less than the threshold (>10 K) required to adversely affect comfort, although fell within the range where localised thermal sensation could be reported by proximate occupants [14]. The presence of a living wall could therefore result in occupants experiencing beneficial thermal sensations and diversity [15]; provided their presence is within the immediate zone of influence. The likelihood of the case study building occupants encountering this however is minimal, given that at higher floor levels proximity is restricted by the installation's default arrangement (presence of a void). The beneficial experience of living wall associated thermal diversity is therefore unavailable to this building's occupants.

5. CONCLUSION

Previous studies had presented experimental evidence to suggest significant thermal benefit from exterior vertical greening application. This study presents in-situ monitoring results in relation to an indoor atrium and semi-outdoor court to characterise living wall influence on the microclimates of sheltered conditions. The results highlighted a surface proximate cooling and humidifying influence at the indoor study (maximum AT: M = 0.3 K and RH: M = 5.5%), and greater influence at the semi-outdoor study (maximum AT: M = 0.9 K and RH: M = 13.7%). This disparity in influence suggests that greater the degree of shelter (enclosed system), the weaker the hygrothermal influence is likely to be. This is mostly attributed to the reduced influence of atmospheric advection, where in higher exposure conditions latent and sensible flux advection enhances transpiration associated microclimate influence.

The indoor study results established that most of the humidity generated from transpiration is repurposed to maintain good foliage health during the summer. This is particularly significant in indoor conditions where ambient RH is maintained at much lower values than would be required for evergreen plants. In general, the potency of hygrothermal modifications characterised by horizontal distribution was most apparent within the 1-2 m zone from installation surfaces. Beyond this range, other phenomena such as the stack flow at the indoor atrium, seem to cause interference and mixing to disrupt horizontal distribution. Hygrothermal gradation with installation height was also observed at both case studies, although the semi-outdoor court presented a wintertime inversion explained by its arrangement and resultant thermal exchanges. In general, vertical canopy temperature distribution is significantly influenced by exposure to irradiation loading, with remaining contribution from intermediate level thermal sources and sinks.

Although ST differences are not potent enough to cause radiation asymmetry associated discomfort, they are likely to be potent enough to present thermal sensation and diversity to occupants, which highlights an area that warrants further investigation. The design and arrangements of the installation at the indoor case study however precludes such benefits from being experienced by its building occupants at present. This in turn highlights the necessity for designers to take account of the proximity influence and increase building occupant access at future projects.

The monitoring study presented in this conference paper was subject to several limitations. A key limitation of carrying out in-situ monitoring was the inability to place sensors at ideal locations. At the indoor study for example, sensors were suspended across the atrium only where support structures were available. Furthermore, both studies were in occupied buildings, which meant that monitoring schedules had to be modified to not disrupt their day-to-day operation. This was critical at the indoor study, where the building has multiple occupancy and significant occupant and visitor traffic. Caution must also be raised here in relation to the interpretation of observations. Point-based ST readings for example are not truly representative of the distribution diversity of plant canopies, with quantitative thermography advocated as a comprehensive alternative where available.

ACKNOWLEDGEMENT

The work described in this paper is part of a doctoral studentship funded by the UK Engineering and Physical Sciences Research Council [1930753].

REFERENCES

1. K. Gunawardena & K. Steemers, Living walls in indoor environments. *Building and Environment*, 148 (2019) 478–487.
2. K. R. Gunawardena & T. Kershaw, Green and blue-space significance to urban heat island mitigation. In S. Emmit, & K. Adeyeye,eds., *Integr. Des. Int. Conf.* (Bath: University of Bath, 2016), pp. 1–15.
3. R. Collins, M. Schaafsma, & M. D. Hudson, The value of green walls to urban biodiversity. *Land Use Policy*, 64 (2017) 114–123.
4. K. R. Gunawardena, M. J. Wells, & T. Kershaw, Utilising green and bluespace to mitigate urban heat island intensity. *Science of the Total Environment*, 584–585 (2017) 1040–1055.
5. K. Gunawardena & K. Steemers, Living wall influence on microclimates: an indoor case study. *CISBAT 2019, Spec. Issue J. Phys. Conf. Ser.* (IOP Science, 2019).
6. L. Pérez-Urrestarazu, R. Fernández-Cañero, A. Franco, & G. Egea, Influence of an active living wall on indoor temperature and humidity conditions. *Ecological Engineering*, 90 (2016) 120–124.
7. I. Susorova, P. Azimi, & B. Stephens, The effects of climbing vegetation on the local microclimate, thermal performance, and air infiltration of four building facade orientations. *Building and Environment*, 76 (2014) 113–124.
8. R. W. F. Cameron, J. E. Taylor, & M. R. Emmett, What's "cool" in the world of green façades? How plant choice influences the cooling properties of green walls. *Building and Environment*, 73 (2014) 198–207.
9. G. Öquist & N. P. A. Huner, Photosynthesis of Overwintering Evergreen Plants. *Annual Review of Plant Biology*, 54 (2003) 329–355.
10. H. Lamberts, F. Stuart Chapin, T. L. Pons, H. Lambers, F. S. Chapin, T. L. Pons, H. Lamberts, F. Stuart Chapin, & T. L. Pons, *Plant Physiological Ecology*, Second (Springer New York, 2008).
11. CIBSE, *Guide A: Environmental design*, 8th ed (Norwich: Chartered Institution of Building Services Engineers, 2018).
12. K. Gunawardena & K. Steemers, Urban living walls: reporting on maintenance challenges from a review of European installations. *Architectural Science Review*, 0 (2020) 1–10.
13. R. Fernández-Cañero, L. P. Urrestarazu, & A. Franco Salas, Assessment of the cooling potential of an indoor living wall using different substrates in a warm climate. *Indoor and Built Environment*, 21 (2012) 642–650.
14. P. O. Fanger, B. M. Ipsen, G. Langkilde, B. W. Olessen, N. K. Christensen, & S. Tanabe, Comfort limits for asymmetric thermal radiation. *Energy and Buildings*, 8 (1985) 225–236.
15. K. Steemers & M. A. Steane, *Environmental diversity in architecture* (London: Spon Press, 2004).