Small-scale experiments of Seasonal Heat Stress Attenuation through a Combination of Green Roof and Green Walls

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Abstract

New and retrofitted green roofs and green walls (GRGW) represent an opportunity to attenuate excessive heat produced in increasingly densely developed urban environments. This paper reports on the results of an original experiment in Sydney Australia in 2016 to evaluate seasonally the heat stress attenuation through green roofs and green walls. Data was collected from mid-summer 2016 (January) to early summer (November 2016) the following season. Two scaled-down structures representing a considerable percentage of housing stock were used to compare heat attenuation in a traditional design compared to a structure covered with a lightweight GRGW on two elevations. Importantly, the results inform our knowledge and understanding of the fluctuations in GRGW performance over an extended period. The combination of relative humidity and temperature plays an important role in establishing heat stress levels in terms of Wet Bulb Globe Temperature (WBGT). The higher levels of WBGT occurred in summer, whereas the lower levels occurred in winter. The WBGT of both prototypes was similar during winter, showing no significant relevance of GRGW for heating an indoor environment. However, during the summer the vegetation had a major role in reducing WBGT. Heat stress is seasonally evaluated according to the percentage of the time, which the thresholds for different metabolic activities are reached. During warm conditions GRGW attenuated heat stress and the associated health-related risks substantially.

Keywords: Green roofs, Green walls, WBGT, Heat stress.

Highlights

- Use of lightweight modular vegetated systems applied on roof and walls
- The role of green roof and green walls in thermal stress attenuation
- Health stress assessment according to WBGT parameter is evaluated seasonally
- Mitigation of health risks associated with heat stress by modular vegetated systems

1 Introduction

The physical characteristics of inner-city areas are typically high-rise, high-density commercial and residential buildings. The scale of the buildings often requires air conditioning to maintain comfortable temperatures during summer periods, with excess heat deposited into the streets. External building envelope materials are typically specified with colours that absorb heat and transfer this to the interior of the building (Lam et al., 2005). Furthermore, excessive areas of glazing on facades, associated with dark coloured roofing materials, allows considerable amounts of heat to transfer and causes heat gain to occur in buildings.

Due to the increase in global temperatures, heat waves are expected to become more intense and frequent in urban environments, as a result of the replacement of vegetation by concrete and asphalt, which alters the radioactive energy fluxes (Castleton, 2010; Parizotto and Lamberts, 2011) and decreases surface moisture levels available for evapotranspiration. Secondly, changes in the near-surface airflow due to the complex geometry and density of streets and buildings, and finally heat produced by human activities add to urban heat loads. Collectively the changes, known as the “urban heat island effect” (UHI), are responsible for temperature differences observed between urban and rural areas (Laadi et al., 2012). The UHI comprises one of the urbanisation effects on the urban climate, resulting in higher urban temperatures when compared to surrounding non-urban areas (Imran et al., 2018).

A solution to mitigate these problems may lie in the retrofit of existing built environments with green roofs and green walls (Osmond and Irger, 2016; Herreira-Gomez et al. 2017). Besides improving urban air quality (Yang et al., 2008), green roofs and green walls reduce heat fluxes, and promote temperature attenuation and building energy consumption (Castleton, 2010). Given these circumstances, questions arise such as: what is the seasonal variation of heat stress attenuation through a combination of green roofs and green walls (GRGW)? An understanding of the variations in heat stress attenuation, combined with statistical demographic data, will enable design for optimum outcomes in terms of health for local populations.

1.1 ***GRGW and heat stress attenuation***

Heat stress is associated with adverse health outcomes, including higher rates of all-cause and cardiovascular mortality and emergency hospitalisations, across a range of geographical regions worldwide (Ye et al., 2011; Laaidi et al., 2012; Hondula and Barnett, 2014).

Green roofs are capable of reducing heat stress in urban environments. A green roof coverage of 50% and 90% improved the human thermal comfort at pedestrian and roof surface levels (Imran et al., 2018). Depending on climate condition, Lin et al. (2013) reported that green roofs could reduce outdoor roof surface temperatures by about 42%, contributing to the attenuation of indoor temperatures.

According to Feng et al. (2014), living walls increase the thermal performance of buildings, due to the insulating effect of the air between the facade and the living wall. Cameron et al. (2014) and Castiglia Feitosa and Wilkinson (2018) showed that GRGW provide a layer of insulation that reduces heat stress and thereby reduce energy consumption for cooling environments. The energy savings provided by GRGW can reduce the amount of pollutants released to the atmosphere, improving air quality and mitigating greenhouse gases responsible for global warming, which increases the impact on human health in terms of heat stress (Castleton, 2010; Coutts et al., 2013; Wilkinson and Torpy, 2018).

GRGW have been used as a solution to offset the impact of the urbanisation process, providing indoor thermal comfort by avoiding heat absorption in building facades and rooftops. As noted by dos Santos et al. (2019) green roof technology can be an alternative for energy savings due to its capacity to reduce indoor temperatures. In terms of health aspects, the attenuation of heat stress reduces the likelihood of health-related risks associated with heat exposure, especially in humid tropical climates, where the humidity effects superpose to high temperatures.

Several indices have been proposed for heat stress evaluation (Webber et al., 2003). Heat stress indices comprise a single value that integrates the effect of thermal environmental parameters that reflect the thermal strain experienced by an individual. According to Epstein and Moran (2006) amongst humidity, radiant temperature, and air velocity, temperature is rarely the most important cause of heat stress.

Many indices are available in the literature, see Epstein and Moran (2006), Webber et al. (2003), Parsons (2006), Lemke and Kjellstrom (2012), Havenith and Fiala (2015), Schminder and Gårdhagen (2018) and Wang et al. (2018) among others. The National Institute for Occupational Safety and Health (NIOSH) emphasises that the calculation of heat stress must be simple and predictive of workers' physiological strain and therefore the Wet Bulb Globe Temperature (WBGT) index meets these requirements (Webber et al., 2003). WBGT is one of the most used heat stress indices and is recommended by many international organisations to evaluate exposure to hot environments (Webber et al., 2003; Epstein and Moran, 2006; Parsons, 2006).

1.2 ***Objectives***

According to Huo et al. (2019) if green strategies are adopted during the site planning process, then problems related to high-energy use for cooling indoor environment can be managed in the early stage of design and construction. However, most existing buildings were not designed considering a Green Building perspective, which implies some structural designs are incapable of supporting the extra loads imposed by green roofs. Thus, this work adopted a modular and lightweight system, which could be a feasible application to retrofit and install new GRGW walls at city-scale, which could mitigate environmental problems associated with dense urbanisation. The modular system comprises a relatively low-cost technique. It is lightweight, does not require structural reinforcement and thus, no cost is incurred for additional structural reinforcement of the buildings where these lightweight GRGW can be retrofitted. In addition, the modular characteristic allows the use of reusable materials as plant containers. For example, as described in the methodology, the present work used document holders for the green wall assemblage. Affordable, reusable and unwanted materials can mitigate the drawback of high-costs of green roofs cited by Sangkakool et al. (2018).

Imran et al. (2018), dos Santos et al. (2019), and Lee and Jim (2019) highlighted the thermal benefits of GRGW. However, these studies did not consider the combined effect of GRGW over a long-term perspective. Lee and Jim (2019) evaluated separately the effect of green walls comparing the surface and air temperatures of outdoor and indoor environments during a three-non-consecutive day experiment under sunny, cloudy and rainy meteorological conditions. Imran et al. (2018) evaluated the single influence of green roofs on UHI mitigation (outdoor condition) in terms of UTCI (Universal Thermal Climate Index) over a 3-day period. dos Santos et al. (2019) monitored indoor temperature and relative humidity for 15 days; however, the thermal performance of the green roofs is expressed only in terms of temperature.

This paper reports a long-term analysis considering the seasonal influence (from summer to spring in Sydney, Australia) of green roof and green walls (GRGW) on attenuating health risks associated with heat stress in indoor environments. Rather than considering the single influence of the temperature, a WBGT index was used to provide a quantitative analysis of heat stress as a simultaneous function of environmental factors such as temperature, relative humidity, air velocity, and radiant temperature.

Two scaled-down structures, reflecting a considerable percentage of Australian housing stock, was used in the experiment to compare heat stress attenuation in an uncovered traditional design and a structure covered with a modular lightweight GRGW using affordable and low-cost materials.

2 Methodology

The methodology takes into account the use of adaptive technologies that enable urban environments to reintroduce some of the former natural vegetation conditions to offset some of the negative effects of urbanisation. A lightweight modular system that allows off-site planting and maintenance was adopted. The attenuation of heat stress is performed by comparing two identical dwellings in a scaled-down prototype, where one prototype was covered with a GRGW as shown in Figure 1.

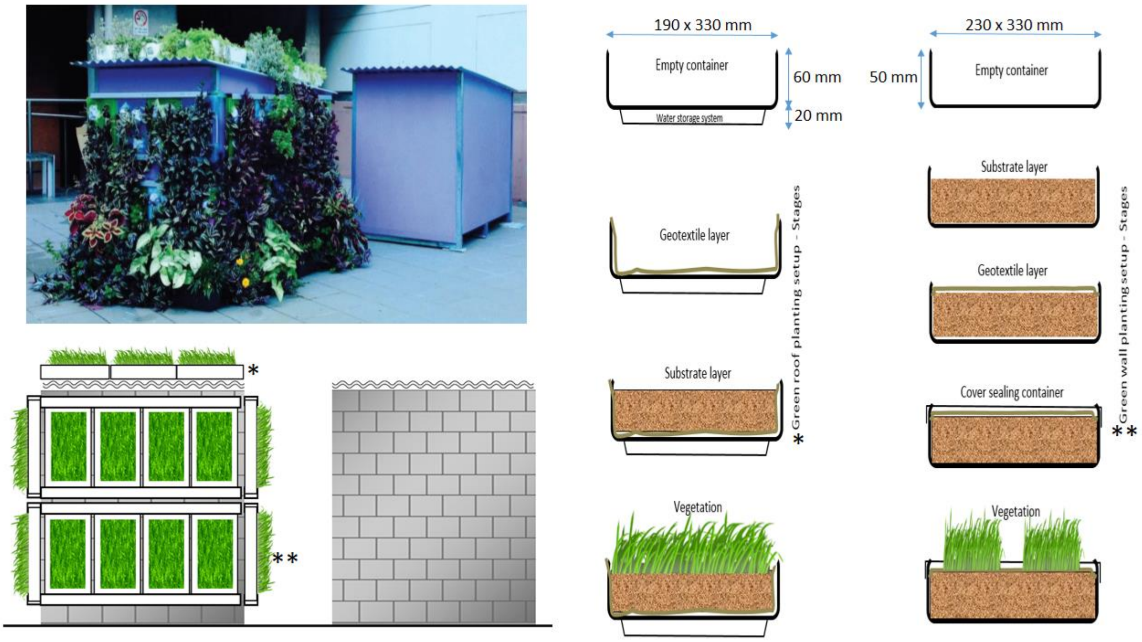

Figure 1: Green roof and green walls experimental setup.

This research evaluated the thermal benefits of the combined effect of GRGW in prototypes that represent typical uninsulated timber frame Australian housing constructions at the University of Technology Sydney (UTS), Australia. In the former work presented by Castiglia Feitosa and Wilkinson (2018), the heat stress was assessed by Heat Index (HI) and did not comprise a seasonal analysis of the dataset. In the present work, the thermal benefits of the vegetation were evaluated seasonally in terms of attenuation on heat stress, comparing the WBGT parameters between the vegetated (VEG) and the non-vegetated (NVEG) prototypes.

Similar to studies performed by Pandey et al. (2013), La Roche and Berardi (2014), Djedjig (2015) and Collins (2017), the thermal stress was undertaken using prototypes, aiming to limit costs and excess loading applied to the existing structure where the experiment was performed.

2.1 Experimental setup and planting characteristics

The same experimental setup as presented by Castiglia Feitosa and Wilkinson (2018) in Sydney was used in the work presented here. In summary, the dimensions of the timber frame structure prototypes were: 150cm length; 120cm width; 100cm front height; 120cm back height. The estimated albedo of the prototype walls (dark blue) and the galvanised steel roof coverings were 0.3 and 0.24 respectively (Designing Buildings, 2018).

As depicted in Figure 1, the GRGW comprised a modular system previously planted with succulent species, using 5cm soil layers.

The green roof was assembled in rectangular plastic containers (190 x 330 mm), where a permeable fabric separated the soil from the drainage layer and water storage system to avoid loss of soil particles. The green wall system was designed using plastic lid boxes (230 x 330 mm) with six circular openings drilled into the lid, in a threerow and two-column array. In this case, there is no storage water system and the geotextile fabric covers the soil before being sealed by the cover of the container box. Small cuts made into the fabric allow the insert of the vegetation in the system. After the planting stage, the green roof modules were placed onto a single roof covered in metal sheeting, while the green walls modules were placed in “U” shaped metal profile channels fixed to the walls. The vegetation covered about 100% of the roof and 85% of the walls.

The vegetation was composed of succulents species such as *Crassula Lycopodioides*, *Echeveria, Tradescantia*, *Sedum* and *Pachyveria*. However, the walls of the prototype were predominately covered with *Tradescantia*. Succulents represent a group of drought-tolerant plants that possess a Crassulacean Acid Metabolism (CAM) responsible for reducing daytime evapotranspiration by closing their stomata shut during this time but opening them at night for carbon dioxide (CO_2) uptake. The choice of succulents relies on their low maintenance characteristics in terms of water needs. The experimental setup needed only sporadic watering, during long periods of no rainfall.

2.2 Data collection

Heat stress was evaluated by WBGT index, based on registers of temperature and relative humidity (RH) measured simultaneously inside each prototypes by two individual USB data logger Extech RHT10, with the following specifications:

- Ranges: -40 to 70°C and 0 to 100%
- Resolution: 0.1°C and 0.1%
- Accuracy: ± 0.5°C and ± 3%

The data collection comprised summer (19/01/16-21/03/16 ~61 days), autumn (21/03/16-21/06/16 ~92 days), winter (21/06/16-21/09/16 ~92 days) and spring (21/09/16-14/11/16 ~55 days) periods. The measurements were taken every 30 minutes and comprised, for each prototype, 14,415 data points. The individual data loggers were placed about 700 mm above the floor of each prototype and could be accessed through a 100 mm diameter circular openings positioned in the front facade.

2.3 Meteorological conditions

Meteorological daily data was available from the Bureau of Meteorology Australia (BOM, 2018) and was collected at Sydney airport, about 9 Km away from UTS. Monthly means of temperature, relative humidity and wind velocity from January to November (2016) are depicted in Figure 2, as well as the corresponding WBGT index values, calculated for shaded outdoor conditions (no solar radiation) as described in section 2.4.

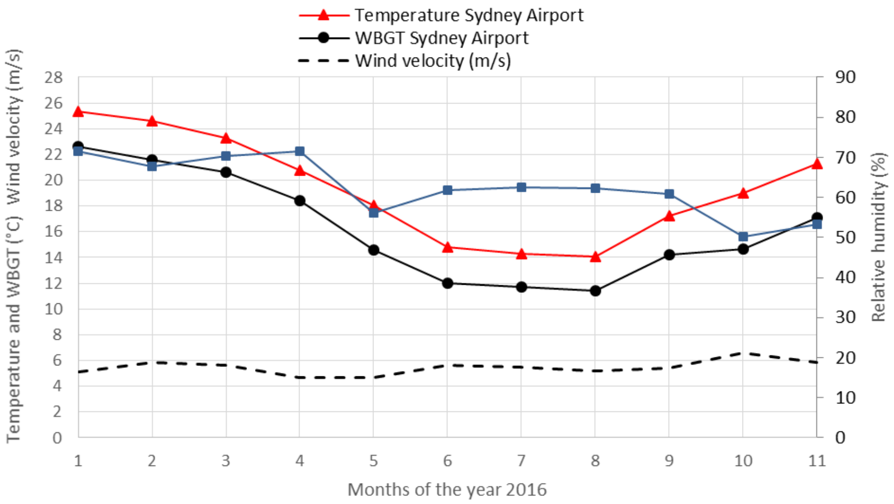

Figure 2 – Sydney airport 2016 monthly means.

2.4 *Quantifying Heat stress in terms of WBGT index*

The calculation of WBGT for indoor purposes as a function of air temperature, humidity and wind speed was performed through an excel spreadsheet that contained a number of Visual Basic macros that takes into account the methodology proposed by Bernard and Pourmoghan (1999) . This methodology has been tested in several locations in the United States (U.S.) with different climates and presented a very good correlation with measured data (Lemke and Kjellstrom, 2012; Grundstein et al., 2015).

The present work evaluated the effect of GRGW in indoor conditions, and thus it was focused on the calculations of WBGT.

According to ISO 7243, the WBGT index is determined for indoor conditions as:

$$WBGT = 0.7\, Tnwb + 0.3\, Tg \quad (1)$$

Where *Tnwb* is the natural wet bulb temperature, and *Tg* is the globe temperature.

However, for indoor calculations, the work performed by Lemke and Kjellstrom (2012), among several methods, recommend the following relationship proposed by Bernard and Pourmoghan (1999) that makes explicit the wind velocity (*v*) between 0.3 and 3 m/s and considers for indoor conditions *Tg* similar to air temperature (*Ta*).

$$Tnwb = Ta - (0.96 + 0.069 \log V)\,.\,(Ta - Tpwb) \quad (2)$$

Substituting equation (2) in equation (1), WBGT for indoor conditions is calculated by:

$$WBGT = 0.67\, Tpwb + 0.33\, Ta - 0.048 \log\, V\, (Ta - Tpwb) \quad (3)$$

In this equation *Tpwb* (psychometric wet bulb temperature) and *Pa* (atmospheric pressure) are calculated according to the following equations where *RH* is the relative humidity.

$$Tpwb = 0.376 + 5.79\, Pa + (0.388 - 0.0465 Pa) Ta \quad (4)$$

$$Pa = RH\ (\%)\ .06107\ \left(\exp\left[17.27\ \frac{Ta}{(Ta+237.3)}\ \right]\right) \quad (5)$$

According to Budd (2008), all variables used in the equations represent a set of specific environmental parameters. *Tg* represents the environmental heat load, *Tnwb* reflects evaporation rates. *Tg* is balanced by inputs of radiant heat and outputs of heat due to the cooling effect of the wind. In other terms, *Tg* measures the combined effect of air temperature, radiant heat, and wind speed, whereas *Tnwb* is regulated by humidity, wind and radiation levels.

In order to evaluate the environmental conditions according to performed activities, many regulatory bodies have proposed WBGT "Permissible heat exposure threshold limits values" (TLVs) for different workload rates. The National Institute for Occupational Safety and Health (NIOSH) published a compilation of TLVs provided by regulatory bodies such as the American Conference of Governmental Industrial Hygienists (ACGIH), the Occupational Safety and Health Administration (OSHA), the American Industrial Hygiene Association (AIHA), and by ISO 7243 “Hot Environments - Estimation of the Heat Stress on Working Man”. These data adapted from NIOSH (2016) for air velocities lower than 1.5 m/s are presented in Table 1 below.

Table 1 – WBGT threshold limit values (TLVs) for different workload rates (Watts - W) according to different regulatory bodies.

Workload/activity	ACGIH	AIHA	OSHA	ISO	NIOSH	Mean values
Resting	--	32.2°C (117 W)	--	33°C (< 117 W)	--	32.6°C
Light	30°C (117-233 W)	30°C (233 W)	30°C (233 W)	30°C (117-234 W)	30°C (≤ 233 W)	30.0°C
Moderate	26.7°C (234 -407 W)	26.7°C (349 W)	27.8°C (234 -349 W)	28°C (234 -360 W)	28°C (234 -349 W)	27.4°C
Heavy	--	--	26.1°C (≥ 350 W)	25°C (360 -468 W)	26.5°C (350 -465 W)	25.9°C
Very heavy	25°C (407-581 W)	--	--	23°C (> 468 W)	25°C (466 -580 W)	24.3°C

Aiming to provide a reference value, the mean of the TLV’s specified limits in Table 1 was adopted to comprise general heat stress limits in the evaluation of heat stress in indoor environments of VEG and NVEG prototypes.

3 Results

Figure 3 introduces a general comparison in colour scale between the indoor WBGT of both prototypes from January to November 2016. Compared to VEG prototypes, higher WBGT levels were evidenced in the NVEG prototypes mostly in the first three months of the year (January to March). From months 6 to 8 (June to August), a WBGT in both prototypes became similar. From October (month 10), higher WBGT levels recurred in the NVEG prototypes. From a statistical point of view, a seasonal analysis can highlight periodically GRGW performance on heat stress attenuation separately from cool to warm conditions, or how efficient a GRGW is on cooling environments over the seasons.

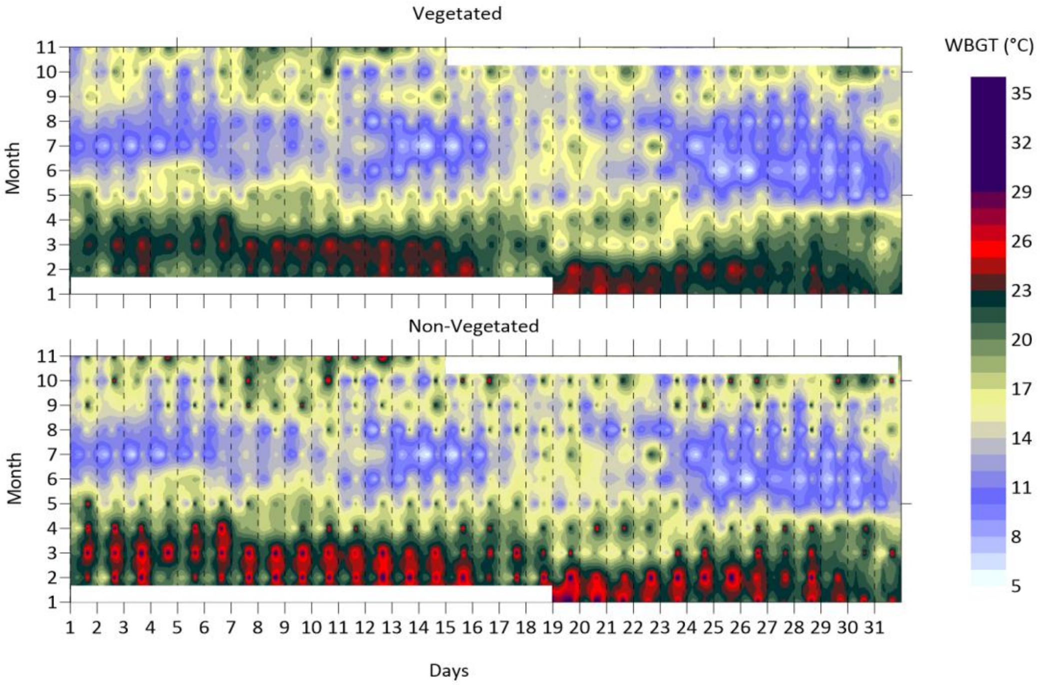

Figure 3 – General WBGT comparison between non-vegetated and vegetated prototypes.

3.1 WBGT seasonal analysis

The line graphs in Figure 4 evaluate seasonally, the indoor WBGT of both prototypes mainly as a function of temperature and RH. The radiant temperature was considered similar to air temperature, due to the absence of radiant heat sources, and the air velocities were set close to zero to simulate the most unfavourable indoor conditions.

The lower lines in each graph represent, simultaneously, WBGT differences between the NVEG and the VEG prototypes. Positive differences indicate higher WBGT levels in the NVEG prototype, whereas negative differences indicate the opposite. On the right side, the histograms show seasonally the frequency distribution of indoor WBGT for the both prototypes.

During summer conditions the highest levels of WBGT were 34.6°C and 27.7°C respectively for the NVEG and the VEG prototypes, whereas the minimum levels were about the same, at 14.7°C and 14.5°C respectively. The differences in WBGT varied from -1.9°C to 8.3°C. Regarding frequency distribution, the WBGT range 22°C - 23.5°C had the highest number of occurrences in both prototypes (35% - VEG and 28% NVEG). However, ranges from 26.5°C occurred 13% and 0.8 % of the time in NVEG and VEG prototypes.

During autumn, the highest WBGT for NVEG and VEG prototypes were 31.8°C and 25.3°C respectively, with the lowest at 6.8°C and 7.1°C. The WBGT differences ranged from -1.5°C to 8.3°C. The WBGT range of 17.5°C - 19°C also had the highest number of occurrences for both prototypes (19% VEG and 16% NVEG). In the VEG prototype, frequencies for WBGT higher than 23.5°C were negligible, whereas for the NVEG prototype, they occurred 4.5% of the time.

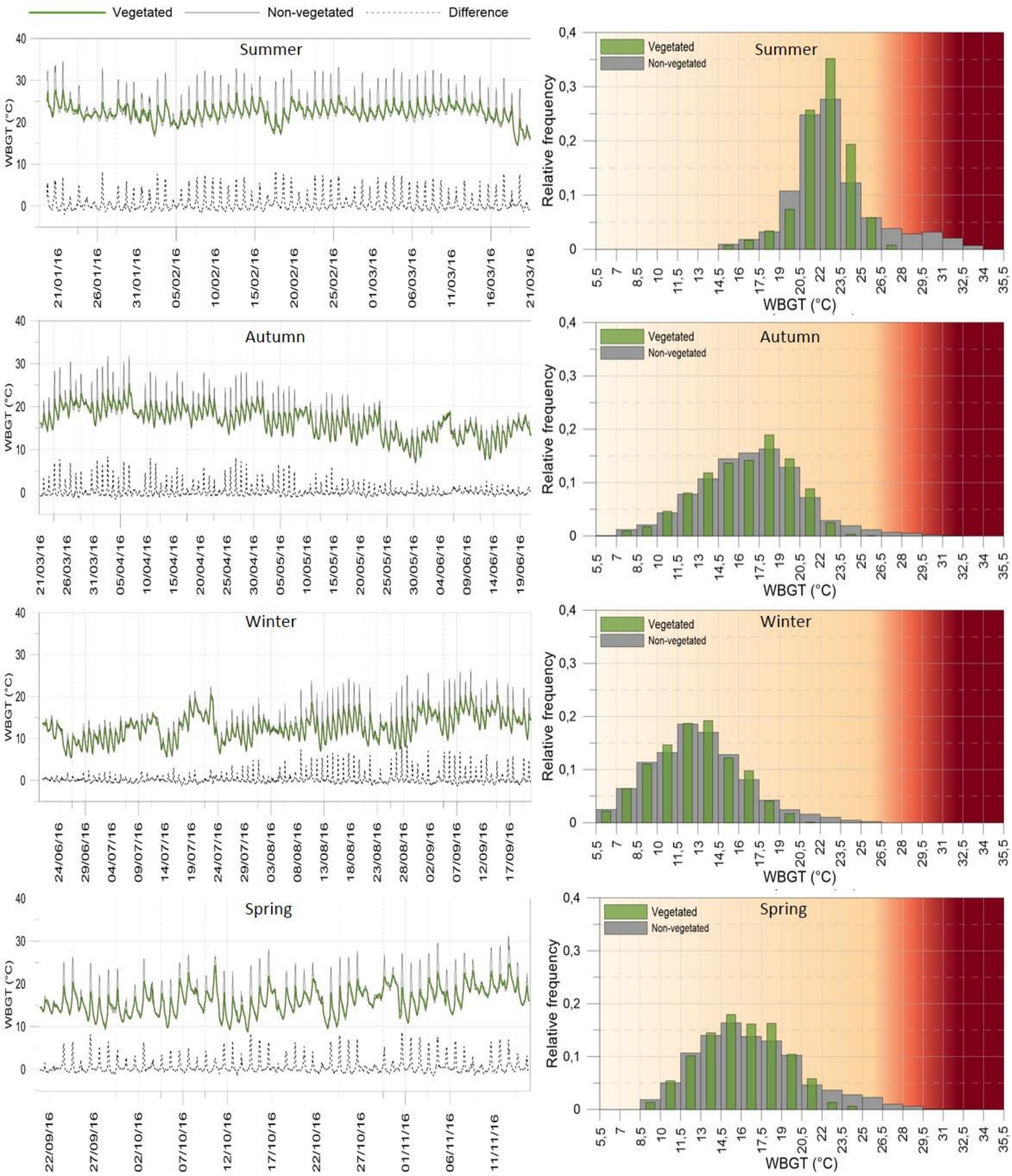

Figure 4 - Seasonal conditions of WBGT over time (left side) and the respective relative frequencies (right side). The lower lines in each graph represent differences in WBGT between the non-vegetated and the vegetated prototypes.

During winter, the maximum values of WBGT were 26.4°C and 21°C, respectively, for the NVEG and the VEG prototypes, whereas the lowest remained close to 5.5°C for both prototypes. The differences varied between -1.4°C and 8.6°C. The highest WBGT frequencies for VEG (19.2%) and NVEG prototypes (18.6%) occurred respectively for ranges 13°C - 14.5°C and 11.5°C - 13°C. However, the WBGT values from 20.5°C practically did not occur for the VEG prototype, but represented 3.3% of occurrences in the NVEG prototype.

During the spring, the maximum and minimum values of WBGT reached 31.1°C and 24.6°C, and 8.6°C and 8.9°C respectively for the NVEG and the VEG prototypes. The attenuation in heat stress in terms of WBGT differences varied from -1.5°C to 8.7°C. The highest frequencies for the VEG and NVEG prototypes were 18% and 16%, and; occurred for WBGT range 14.5°C-16°C. However, WBGT values higher than 23.5°C were negligible for the VEG prototype, but represented 6.8% of occurrences for the NVEG prototype.

The histograms (Figure 3) shift to the left, covering lower WBGT bands from summer to winter, and from this point starts shifting to the right reaching again bands of higher WBGT during spring. Statistically, it was also evident the influence of GRGW on heat stress attenuation as the warm conditions increase. The aforementioned results indicated the trend of GRGW in narrowing the WBGT ranges when compared to NVEG prototypes.

Table 2 presents a summary of the highest and the lowest WBGT differences from summer to spring, as well as the time these differences occurred, and the respective WBGT levels of the NVEG and VEG prototypes. It is worth noting that the highest and lowest WBGT differences did not occur necessarily at the same time as the highest and lowest WBGT levels.

Table 2 - Seasonal analysis. Highest and lowest WBGT differences and the respective WBGT levels in non-vegetated and vegetated prototypes. Diff – differences between non-vegetated (NVEG) and vegetated (VEG) prototypes.

WBGT (°C)	**Summer**				**Autumn**				**Winter**				**Spring**			
	Diff.	**Time**	NVEG	VEG	Diff.	**Time**	NVEG	VEG	Diff.	**Time**	NVEG	VEG	Diff.	**Time**	NVEG	VEG
Highest	8.3	26/01 15:15	32.9	24.6	8.3	02/04 15:45	31.8	23.5	8.6	28/08 15:00	24.2	15.6	8.7	31/10 14:00	26.0	17.4
Lowest	-1.9	21/01 19:45	22.7	24.6	-1.5	04/04 02:45	18.8	20.3	-1.4	07/09 05:00	14.3	15.7	-1.5	13:10 02:30	11,3	12,8

During the summer by comparing WGBT between the prototypes and the respective WBGT differences, the role of the vegetation in heat stress attenuation is evident. During autumn, the influence of vegetation on WBGT is still evident but diminishes as the season progresses towards winter, with WBGT levels in the VEG prototype similar to those in the NVEG prototype. The WBGT differences are negligible in June and July, but start to increase towards spring evidencing the role of GRGW in heat stress attenuation during warm conditions.

The histogram depicted in Figure 5 presents the seasonal relative frequency of WBGT differences between the prototypes. These differences are classified into five different 2°C intervals. Negative differences (higher WBGT in VEG prototype) occur, respectively from summer to spring, 53%, 57%, 52% and 47% of the time.

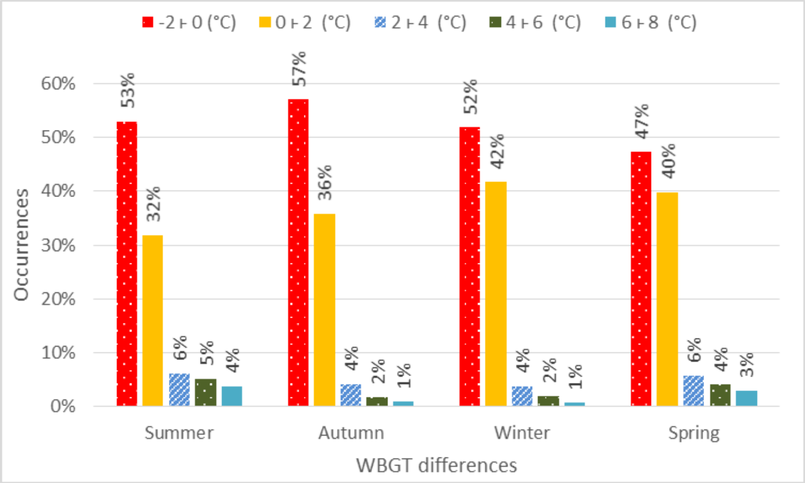

Figure 5 – Seasonal analysis. Percentage of occurrences of WBGT differences between non-vegetated and vegetated prototypes. Values lower than zero belong to the first class, values greater or equal to zero and lower than two belong to second class and so on.

WBGT differences from 2°C occurred respectively from summer to spring 15%, 7%, 7%, and 13% of the time. Autumn and winter presented similar behaviour. Attenuations from 4°C occurred 9% for summer, and 7% for spring, which corresponds respectively to 5.5 days and 3.8 days. The VEG prototype could reduce WBGT from 6°C to 8°C, 4% and 3% of the time in summer and spring respectively. During the autumn and spring, this reduction occurred only 1% of the time.

A statistical z-test analysis was performed at a significance level p = 0.05 (CI=95%) to further analyse weather or not there is a statistical difference between WBGT in both prototypes over the seasons (Table 3).

Table 3 - Result and interpretation - statistical z-test analysis.

	Summer		*Autumn*		*Winter*		*Spring*	
	VEG	*NVEG*	*VEG*	*NVEG*	*VEG*	*NVEG*	*VEG*	*NVEG*
WBGT Mean	22.3	22.9	16.6	16.9	12.7	13.0	16.1	16.7
WBGT Variance	3.7	10.0	10.7	14.5	9.0	12.3	9.2	15.5
z	-8.685		-3.449		-4.263		-6.153	
p-value	5.2E-18		0.000563		0.000020		7.8E-10	
z critical (p=0.05)	1.96		1.96		1.96		1.96	

For all seasons, WBGT between the prototypes was statistically different. However, the differences were more significant during summer and spring indicating the role of GRGW in attenuating heat stress under warm conditions. Among the seasons, the highest WBGT differences between the prototypes were observed in the summer.

3.2 Environmental parameters analysis

Considering the influence of temperature and RH in WBGT values, Figure 6 presents the monthly means of RH temperature and WBGT (upper graphs) for both prototypes, as well as its differences (lower graphs). Positive differences for WBGT and temperature indicate higher levels in the NVEG prototype whereas relative humidity indicates the opposite. The higher levels of RH occurred from summer to mid-autumn and for lower levels in spring.

In the VEG prototype, relative humidity was higher for all seasons. The lower RH differences observed from months 5 to 8 (right lower graph - Figure 6) indicates similar levels for both prototypes.

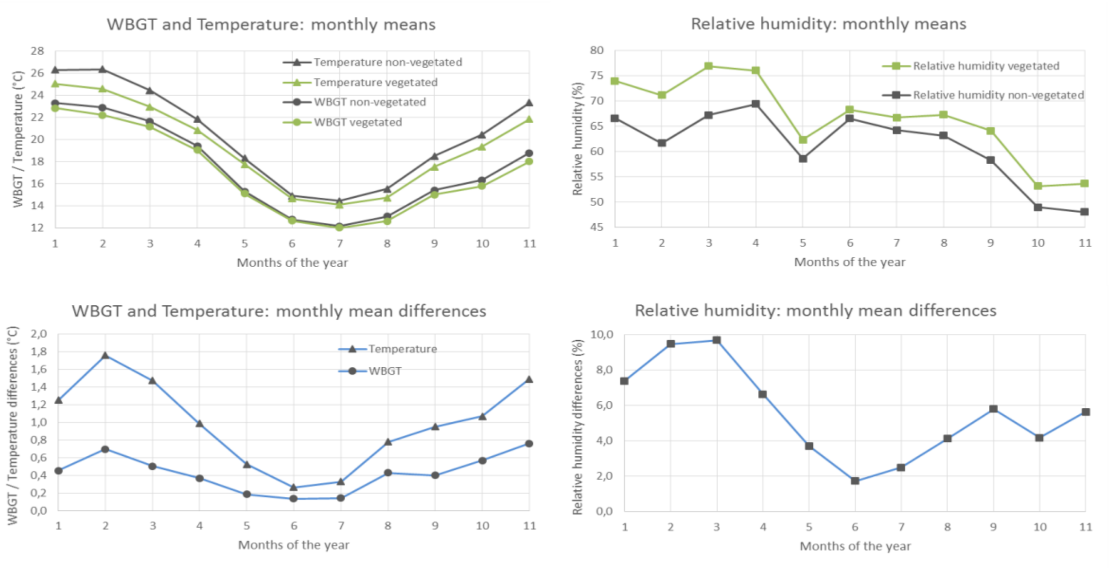

Figure 6 – Monthly means of relative humidity, temperature and WBGT (upper graphs) and respective differences between the prototypes.

In terms of monthly mean temperatures, as depicted in the upper left graph in Figure 6, for both prototypes temperatures are higher in the summer and decrease gradually to minimum levels recorded during wintertime, more specifically from June to August. From this point, temperatures start to increase again during spring. According to the lower-left graph in Figure 6**Error! Reference source not found.**, the monthly mean differences are higher in the summer, indicating higher temperatures in the NVEG prototype. These differences reduce gradually during the autumn and increase again during spring towards summer. During winter, temperature differences reduce substantially, meaning they are similar for both prototypes.

The monthly mean WBGT for both prototypes are similar. However, the indoor WBGT of the NVEG prototype was permanently higher than the VEG prototype. As depicted in Figure 6 (upper left graph), WBGT in both prototypes is higher in the summer decreasing gradually towards winter where the lowest levels occur, especially between June and August. The monthly mean differences in WBGT are higher in the summer, reduce gradually during the autumn, approach zero in the winter, and increase gradually again during spring towards summer.

Figure 7 (upper graph) shows seasonally the maximum, mean and minimum RH, temperature, and WBGT for both prototypes. The RH mean levels are higher for the VEG prototype and decrease from summer/autumn (73.6%) to spring (54.8%). In the case of the NVEG prototype, it varies from 66.0% to 50.1%. The maximum RH levels range from 92.5% to 84.2% and 89.5% to 74.8%, for the VEG and the NVEG prototypes respectively. Minimum levels vary from 38.6% to 19.9% and from 36.3% to 17.6%, respectively.

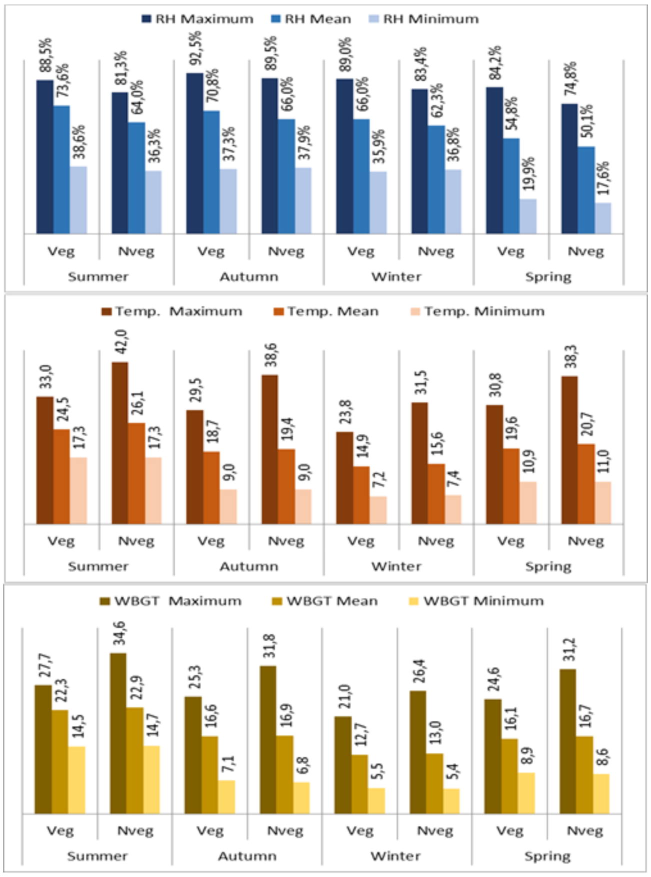

Figure 7 - Seasonal comparison. Maximum, mean and minimum values of relative humidity (RH), temperature and WBGT.

Mean and maximum temperatures (middle graph - Figure 7) for the NVEG prototype were higher than the VEG prototypes for all seasons. Minimum temperatures for the prototypes were the same in summer (17.3°C) and autumn (9°C) and practically identical in winter and spring for the VEG and the NVEG prototypes at 7.2°C and 7.4°C in winter and 10.9°C and 11.0°C in spring respectively.

Maximum WBGT (lower graph - Figure 7), occurred in the summer, the minimum occurred in the winter with maximum and mean levels of WBGT in the NVEG prototype higher than the VEG prototypes for all seasons. Except for summer, the minimum WBGT was slightly higher in the VEG prototype.

3.3 Heat stress and health-related analysis

Regarding indoor environmental conditions for different activities, Figure 8 shows a seasonal comparison between the prototypes, as a function of WBGT thresholds presented in Table 1. This figure shows, for each prototype, the percentage of time in which each activity can be performed. During winter, there would be no restriction on any kind of activity taking place in either prototype. This is also true for the VEG prototype over the autumn and spring periods, but not for the NVEG prototype. In this case, very heavy, heavy and moderate activities can be performed, respectively, 97%, 98% and 99% of the time for the autumn and 94%, 98% and 99% for the spring. Under summer conditions restrictions start in the VEG prototype only for very heavy and heavy activities, allowing such activities 87% and 98% of the time. For the NVEG prototype, these activities can be performed 77% and 86% of the time. Moderate and light activities can be performed 90% and 95% of the time, which means restriction to these basic activities over 10% and 5% of the time (6.1 and 3 days), and restriction of 1% for the presence of people (even resting) without air conditioning.

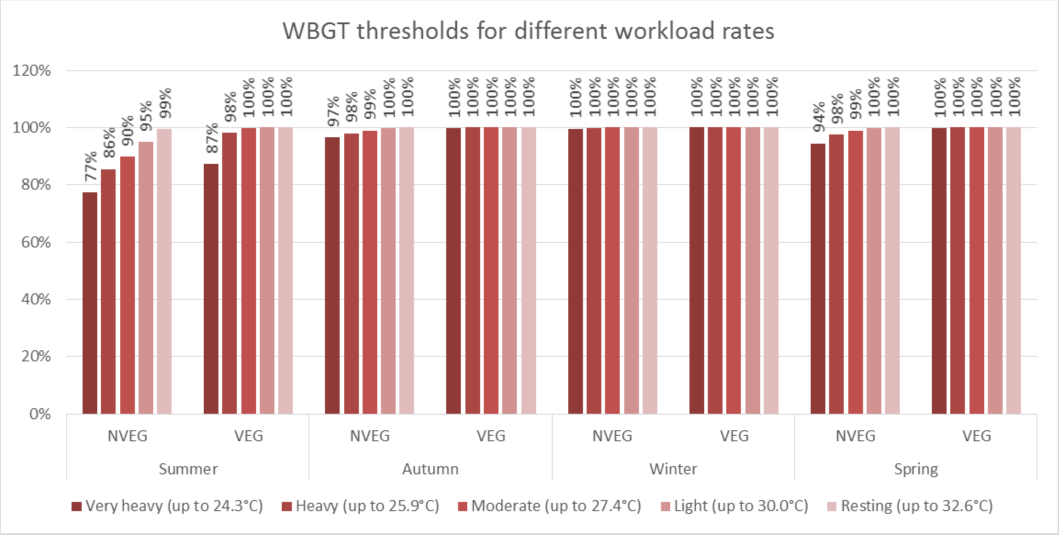

Figure 8 – Seasonal comparison. WBGT thresholds for different activities between the non-vegetated and the vegetated prototypes. The bar graphs indicate the percentage of the time, which each activity can be performed.

4 Discussion

Sydney has a subtropical climate with cool temperatures in the winter and high temperatures in the summer. The heat stress was evaluated comparing indoor WBGT, evaluating seasonally the extent of vegetation in heat stress attenuation in Sydney in a scaled-down timber-framed structure compared to a non-vegetated structure.

The VEG prototype presented the highest efficiencies in improving thermal indoor conditions during warm episodes. Similarly, Castleton (2010), Ziogou et al. (2017) and Cascone et al. (2018) presented similar trends but evaluating the single influence of green roofs in terms of energy savings for cooling. Comparatively to bare roofs, these same authors highlighted that green roofs can keep indoor environments warmer under cooler conditions. However, in the present work, it was not evident the same potential for keeping the indoor environment warmer during cooler episodes, especially during June and July, basically due to the differences in experimental setup characteristics. Cascone et al. (2018) evaluated the green roof performance considering thicker substrates, over a 250 mm structural slab, followed by 50 mm lightweight concrete. In the present case, thinner green roof modules were placed onto a single roof covered in metal sheeting.

Similar to the results presented by Chowdhury et al. (2017), the maximum and mean WBGT values in the VEG prototype were lower than the NVEG prototype for all seasons. Pastore et al. (2017) also corroborated the role of the green roof and green walls in attenuating indoor and outdoor temperatures. However, these authors highlighted that in the case of buildings, green roofs can provide thermal comfort only in the floor below the roof.

Considering the diurnal variations, the efficiency of vegetation in providing cooler conditions was evaluated taking into account the WBGT difference between the prototypes. Positive differences indicated the potential for cooling and negative differences the potential for avoiding heat loss from indoor to outdoor environment. The highest positive differences occurred between noon and sunset, and the lowest (negative) occurred during the night-time or early morning. This trend was similar to the observed by dos Santos et al. (2019).

The potential of GRGW in improving thermal indoor conditions lies basically on the shading effect provided by the vegetation and on the thermal insulation properties of the elements that comprise the green roof and green walls systems (Fioretti et al., 2010). These systems increase the thermal performance of the buildings, evaluated in terms of U-value parameter, that indicates the heat gain or heat loss. Thus, higher U-values are related to worse insulation properties. In a non-insulated building, green roof coverage increased the insulation, reducing the U-value 50% (Wong et al., 2003). The vegetated system on roofs or walls is responsible for attenuate heat exchanges and for producing an evaporative cooling process due to evapotranspiration. The vegetation provides shading and also absorbs solar radiation in a photosynthetic process. Besides, according to dos Santos et al. (2019) the soil absorbs and stores heat during daytime, and releases it slowly during the night, delaying and cushioning the heat transfer process.

Similar to observed by Chowdhury et al. (2017), relative humidity and temperature influence WBGT levels. The maximum, mean and minimum levels of RH are always higher in the VEG prototypes, indicating extra moisture supply provided by the vegetation, likely due to evapotranspiration. The higher RH levels in the VEG prototype offset the effect of temperature attenuation promoted by the vegetation, with WBGT similar in both prototypes. In terms of the monthly WBGT mean, the effect of vegetation was negligible in cooler months, due to the combination of cooler and similar levels of temperatures and RH in both prototypes.

The VEG prototype had a better performance in WBGT attenuation during summer (histogram WBGT attenuation). To provide a quantitative evaluation of the WBGT differences, it is important to have an understanding of which levels of WBGT these attenuations refer to. For instance, compared to the NVEG prototype (Table 2), a WBGT attenuation promoted by the vegetation of 8.3°C (NVEG 32.9°C x VEG 24.6°C) in summer is much more relevant for health impacts than the same attenuation of 8.7°Cin winter (NVEG 24.2°C x VEG 15.6°C). As presented in Table 1 these WBGT ranges are much less restrictive for many indoor activities.

In accordance with Huo et al. (2019), the results are evidence of the advantage of using natural elements (plants) to maintain thermally comfortable environments to enable the performance of various indoor activities. In terms of WBGT, the combination of GRGW presented a significant role in attenuating heat stress and health-related risks categorised according to different workload activities performed in indoor environments (Table 1). The VEG prototype had no restriction for any activity from autumn to spring but presented some restrictions to “very heavy” and “heavy” activities in the summer period. For the NVEG prototypes, only during the winter, no restrictive conditions occurred. The restriction for activities was not significant in the autumn and spring but increased substantially in the summer. During the summer, activities that can be partially performed in the NVEG prototype have no restriction in the VEG prototype. The same trend was found by Chowdhury et al. (2017). In a warm tropical season, green roofs improved significantly indoor thermal conditions, reducing environment temperatures and WBGT. Thus, besides the several benefits of adopting a green building design, the improvement of thermal comfort by GRGW brings direct benefits to human health.

5 Conclusion

The highest WBGT differences occurred in the afternoon whereas the lowest were common during the night-time and early morning. Overall, the differences between indoor WBGT seem to be much more pronounced during summer periods, thus, there was a considerable improvement in the thermal conditions of the VEG prototype. While for other seasons, the effect of the vegetation plays an important role in providing heat stress attenuation, during winter, the effect of vegetation is not so relevant. Additional studies are necessary to evaluate the effect of green roof and/or green walls in attenuating heat stress under tropical conditions, combining high levels of temperature and relative humidity.

The combination of green roofs and green walls comprised an effective alternative to approximate adverse indoor thermal conditions to healthier WBGT ranges. Acknowledging the role of the vegetation in heat stress attenuation, considering the rising trends in temperatures and increased density of urban development, the urban heat island is set to increase the numbers of people, particularly the young and old, being adversely affected by heat stress. One way of mitigating these adverse environmental impacts and enhancing environmental sustainability is the wide-scale adoption of new and retrofitted green roofs and walls, using a modular, lightweight system that comprises simple and affordable technologies, allowing the use of easily accessed and reused materials.

Moreover, the effect GRGW in promoting thermal comfort leads to energy savings for cooling indoor environments, and comprises a good solution towards sustainable and environmental goals, reducing carbon demand to generate energy. GRGW if applied in large scale may also work as carbon sink during the vegetation establishment process, offsetting the effects of climate change. However, further research is necessary to evaluate this potential.

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