A green experiment conducted in the tropical climate

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ABSTRACT: Plants are the intervention between buildings and climate since they can benefit buildings by modifying the micro-climate. The foliage density of plants, or more accurately the Leaf Area Index (LAI), is the key to govern the magnitude of such intervention at the micro-level. In order to uncover the interrelationship between LAI values and the surrounding climatic parameters, an experiment has been carried out in Singapore. A horizontal setting and a vertical setting have been set up to simulate the introduction of greenery on roofs and building facades. Plants with different LAI values were measured at the two settings. The interrelationship between LAI values and climatic parameters has been defined by regressions which are derived from the experimental data. A new concept, green sol-air temperature, was developed based on the empirical data. The possible thermal benefits of plants placed around buildings were estimated by the new concept finally.

Keywords: plants, buildings, climate, LAI value, thermal benefit, green sol-air temperature

1. INTRODUCTION

Buildings, climate and vegetation are the three indiscrete components which can be easily found in a built environment. The interactions among the three components are crucial for some current environmental issues.

Plants make up a city's "urban forest" and provide many environmental and social benefits in cities. These tangible benefits have been summarized by Johnston [1] who believes that plants can clean the air, improve the climate, slow down stormwater runoff, clean rainwater, provide habitats for wildlife and last but not least, being a good investment in a built environment. However, the city greens are threatened by the rapid development of cities where the buildings and the vegetation become two competitors in terms of land use. The blocky and angular buildings are always replacing the soft shapes of trees, shrubs and grass with asphalt, brick, concrete and glass. It is always a dilemma in a city that more buildings should be constructed to meet the requirement of an increasing population and more land should be reserved for landscape/greenery to maintain the ecological health of a city.

Climate, especially sunlight, temperature and precipitation, is one of the major ecological forces affecting the abundance, location, and health of plants. The climatic zones determine what types of plants can survive in the region. Although generally regarded as a function of the climate, plants can in turn influence the local or the site climate. They can improve the climate, especially the micro-climate through providing a shelter from the sun and wind, decreasing the air temperature and increasing the humidity.

Finally, climate has some great impacts on typologies, performances and energy uses of buildings. Inversely, buildings can influence climate. Its impact is limited for an isolated building but magnifying tremendously for a city. The result is that the temperature in a built environment is higher than its suburbs and it is the well-known Urban Heat Island (UHI) effect. Besides the higher temperature, Bridgman [2] also believed that the lower relative humidity (but the higher absolute humidity), higher incidence of fog, lower wind speed (but it is strongly influenced by the orientations of buildings and the street canyons), greater precipitation and cloudiness can be experienced in cities as compared with their surrounding countryside.

To further understand the complex interactions of the three fundamental components in a building environment, a conceptual model is proposed (see Figure 1). The model consists of not only the three components but their interactions (PB, PC, BC and CB). PB is the amount of vegetation introduced into a built environment. It could be enforced when more greenery is introduced into the built environment. PC is the ability of plants to control the climate. BC and CB are the interactions between climate and buildings.

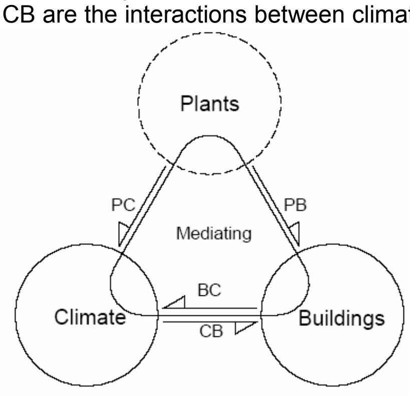

Figure 1: Model of environment (plants is considered to be the major component of environmental control).

Two hypotheses are subsequently generated from the model (see Figure 2). When climate and buildings are largely intervened by plants, the overlapped shaded area between them is decreased which means less conflicts are incurred or less active energy is consumed to mitigate the conflicts (see Hypo I). On the other hand, the shaded area is expanded when the influence of plants is less on climate and buildings. It indicates more negative conflicts happen or more active energy is used for mitigating the negative effects (see Hypo II).

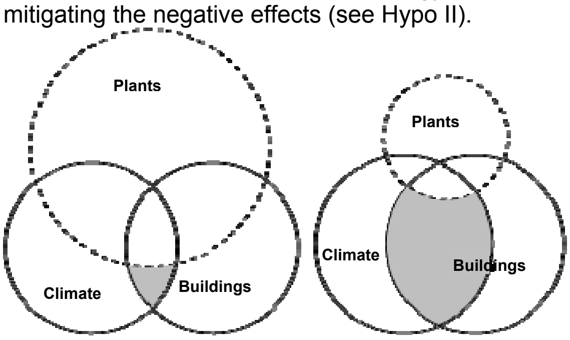

Figure 2: Graphical interpretation of hypothesis I (left) and hypothesis II (right).

Three critical variables, which are the climatic impacts (PC), amount of plants (PB) and the conflict (BC+CB), should be quantitatively evaluated in order to build a harmony city environment with suitable amount of introduced plants and minimal conflicts between buildings and climate. Many researches had been carried out in order to meet the objective in Singapore [3]. It is encouraging that the two hypotheses are proven to be correct and plants do benefit the built environment at both the micro and the macro scale in the tropical climate. However, there is still a lack of simple method to predict such improvement.

2. GREEN SOL-AIR TEMPERATURE CONCEPT

The concept of sol-air temperature was originally developed by Mackey & Wright [4] who combined the convective and radiative heat transfers occurred at an external surface into a single equivalent temperature. There are actually three parts which constitute sol-air temperature. They are 1. ambient air temperature; 2. equivalent temperature increase caused by absorbed incident solar radiation; and 3. equivalent temperature increase/decrease caused by temperature radiation exchange between the surface and its surroundings.

Sol-air temperature is a very good concept which can be calculated from meteorological data together with absorptivity and emissivity of outdoor surface finish. The concept is still being used in the calculation for estimating periodic heat flow through building structures. Some building regulations, such as ETTV, employed similar concept for setting up design criteria.

It is possible to predict the thermal benefits of greenery around building structures according to the principle of sol-air temperature. The only concern is how to incorporate the characteristics of plants into consideration. Therefore, a new concept, green sol-air temperature, is developed by the author. It can be defined as the temperature of the outdoor air which in contact with the shaded surface of any building material that does not directly transmit solar radiation (opaque) would give the same rate of heat transfer and the same temperature distribution through the material as exist with the protected outdoor air temperature and intercepted solar radiation incident upon the surface below/behind plants.

Similarly, the new concept consists of three parts. 1. Bond air temperature within the foliage which is placed around buildings; 2. Equivalent temperature increase caused by absorbed incident solar radiation through foliage; 3. Equivalent temperature increase/decrease caused by temperature radiation exchange between the leaf surface and its surroundings. To work out green sol-air temperature, three unknowns should be considered besides the parameters involved in sol-air temperature. They are:

- Intercepted incident solar radiation
- Temperature of bound air within foliage
- Surface temperature of leaves

The intercepted incident solar radiation can be calculated through the established first principle [5] while the rest have to be estimated by local empirical data. Eventually, the new concept can be integrated in to the conceptual model seamlessly and interpret the model quantitatively.

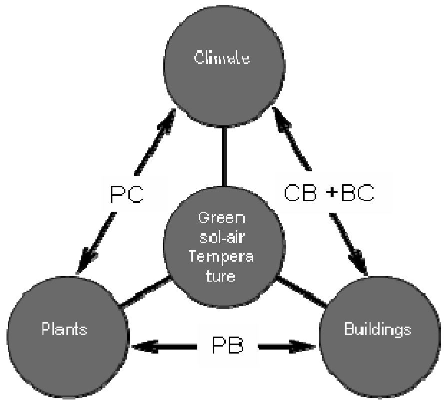

Figure 3: The integration of green sol-air temperature and the conceptual model.

3. GREEN EXPERIMENT AND DATA ANALYSIS

3.1 Experiment design

Basically, green sol-air temperature will not involve the complex thermal behaviors of plants but based on the meteorological data as well as Leaf Area Index (LAI) values. Therefore, some representative regressions should be set up to predict the various thermal behaviors of plants with different LAIs first. An experiment has been designed in order to fulfil the objective. Some significant parameters, such as bond foliage air temperature, leaf surface temperature, soil moisture content, LAIs as well as climatic condition around some selected plants are monitored over a long period of time.

The horizontal set-up consisted of selected potted plants and a measuring post mounted with seven ambient temperature and RH data loggers with an interval of 200mm (see Figure 4). Bond air temperatures (the temperature measured in the immediate vicinity of the foliage) can be measured from just above the soil surface to around 1400 mm. Soil surface temperature and leaf surface temperatures were measured by thermocouple wires at different heights. The density, or more accurately, the LAI values were varied through the arrangement of the potted plants. With the help of the LAI analyzer, three arrangements of LAI values which were 1, 3 and 5 were measured.

Figure 4: Horizontal set-up.

The vertical set-up was made up of a wooden board, rows of plants and related instruments (see Figure 5). The long-axis of the partition board was orientated to face the west and the east orientations which are the unfavoured orientations under the local weather condition. The dimension of the partition board is 1500mm (length) by 1000mm (height). Plotted plants were placed closely in front of the board. The density (LAIs) of plants was varied by changing the rows of plants. In the experiment, single-row, two-row and three-row were tested. The LAI values of the above arrangements were 1, 3 and 5 respectively. Foliage air temperature and RH were measured at a height of 500mm at the two sides of the board behind the potted plants.

Figure 5: Vertical set-up.

Figure 6: the spatial arrangement of the experiment.

The site was occupied by the horizontal set-up, the vertical set-up, the weather station, and the other equipment (see Figure 6). The weather station had been set up near the two experimental set-ups but beyond their possible influential area. Similarly, the vertical and the horizontal set-ups were separated with enough distance to lower any possible mutual-influence.

3.2 Data analysis

To ensure an accurate correlation analysis, a full day has been divided into three phases according to the variation of the intensity of incoming solar radiation as follows:

- From sunrise to 1300 hr – morning;
- From 1300 hr to sunset – afternoon;
- The rest time – night.

Figure 7 shows the correlation analysis of the temperatures measured within the different foliages (LAI = 1, 3, & 5) and the temperature obtained from the weather station set up nearby.

In the morning, the temperatures within the different foliages all have close correlations with the ambient temperatures. First of all, the temperatures measured within the different plants react to the variation of ambient air temperature measured at the weather station. They are all positively correlated to the elevation of ambient air temperature. The sensitivities of the temperatures within the foliages can be distinguished by the gradients of their corresponding trendlines. The elevation of the bond-air-temperature within the plants (LAI = 5) is minimal while that within the plants (LAI = 1) is very apparent.

In the afternoon, the ambient temperatures are decreasing. Accordingly, a trend of decreasing in terms of the gradients can still be observed from the plants varied from the sparse one to the densest one. From noon to sunset, the rate of temperature decreasing within the spare plants (LAI = 1) is faster than those within the plants of higher densities (LAI = 3 & 5).

The correlation at night is the simplest scenario since there is no interference from solar radiation. The temperatures within the foliages still roughly follow the sequence of their respective LAI values. The difference is not very great, especially when the ambient air temperatures measured from the weather station are low during midnight. The measured temperatures within the plants can be even higher than the ambient air temperature during this period. Plants work as barriers between hard surfaces and the microclimate. They have the ability to maintain a relatively stable bond air condition within foliage not only during daytime but also at night. On the other hand, the relatively big differences between the temperatures measured within the different foliages are observed at nightfall since they inherited the corresponding cooling effects during the daytime.

Figure 8 shows the correlation analysis of the temperatures measured within the different foliages (LAI = 1, 3, & 5) and solar radiation obtained from the weather station set up nearby.

In the morning, the variation of the gradients of the trendlines is still in a sequence which follows their corresponding LAI values. The ability of intercepting incoming solar radiation is proportional to the increase in the LAI values. But it does not mean that solar radiation within foliage can be reduced infinitely. On the contrary, it is believed that no obvious improvement can be achieved in terms of decreasing the bond-air-temperature and intercepting solar radiation when LAI value approach a certain level. Unfortunately, such benchmark has not been established in the experiment since there is still a difference between the results obtained from the LAI3 and LAI5 plants.

In the afternoon, time lags between the peak of solar radiation and the peak of the bond-air-temperatures within the foliages can be observed. It has been reflected at the 'high ends' of all the three regressions where the peak solar radiation does not coincide with the peak bond-air-temperatures within the foliages. It seems that the peak bond-air-temperatures occurred when solar radiation reduces from 850W/m^2 to 750W/m^2.

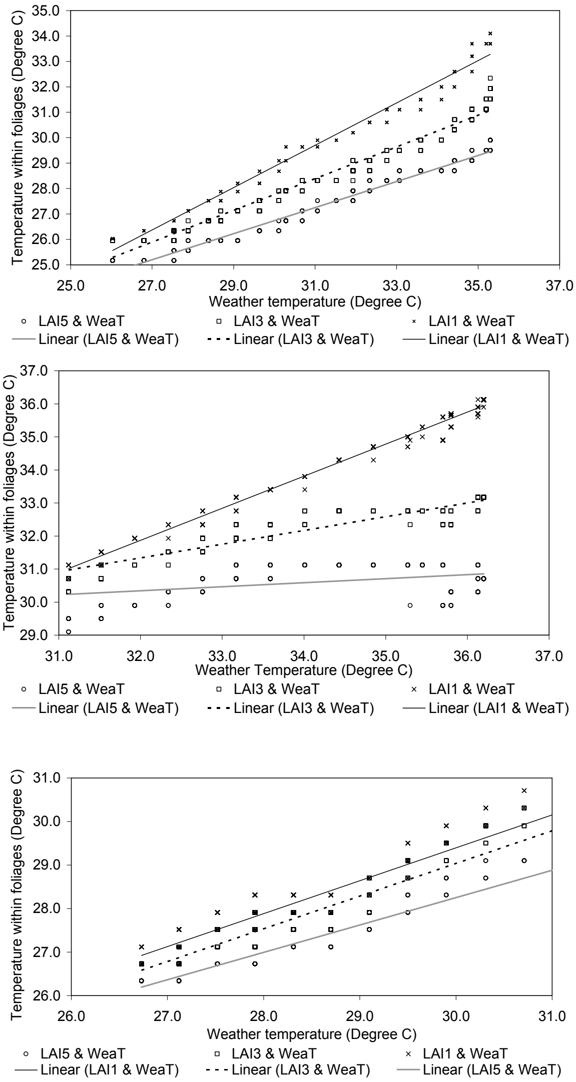

Figure 7: The correlation analysis of the temperatures (LAIx) measured within the different foliages (LAI = 1, 3, & 5) and the temperature (WeaT) obtained from the weather station (Above: morning; Middle: afternoon; Below: night).

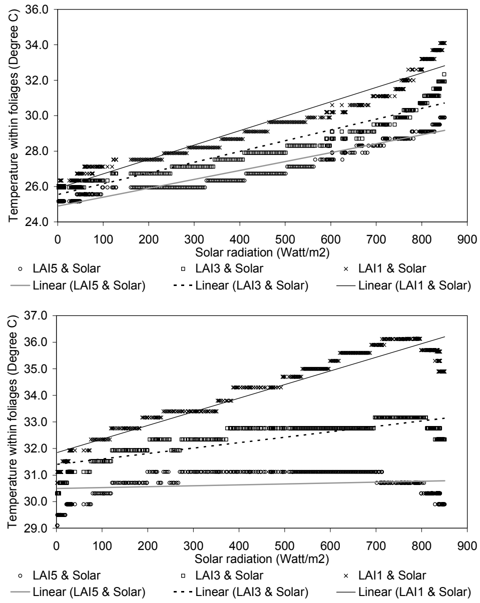

Figure 8: The correlation analysis of the temperatures (LAIx) measured within the different foliages (LAI = 1, 3, & 5) and the solar radiation (Solar) obtained from the weather station (Above: morning; Below: afternoon).

Similar correlation analysis has also been carried out between the temperatures measured within the different foliages (LAI = 1, 3, & 5) and wind speed. However, there is no significant correlation observed.

Based on the above results, some regression models generated through Statistical Package for Social Sciences (SPSS) for both the morning and the afternoon sessions respectively are as follows:

Morning (bond air):

Y_{lai1}	=	$X_1 - [5.786LN(X_1) - 0.0002X_2 - 18.459]$	adjusted r^2 = 0.698 δ = 0.33
Y_{lai3}	=	$X_1 - [12.286LN(X_1) - 0.002X_2 - 39.426]$	adjusted r^2 = 0.933 δ = 0.30
Y_{lai5}	=	$X_1 - [19.56LN(X_1) - 0.001X_2 - 62.638]$	adjusted r^2 = 0.982 δ = 0.20

Afternoon (bond air):

Y_{lai1}	=	$X_1 - EXP(-0.925X_1 - 0.004X_2 + 29.279)$	adjusted r^2 = 0.234 δ = 0.59
Y_{lai3}	=	$X_1 - EXP(0.2X_1 + 0.001X_2 - 6.629)$	adjusted r^2 = 0.942 δ = 0.13
Y_{lai5}	=	$X_1 - EXP(0.087X_1 + 0.001X_2 - 2.819)$	adjusted r^2 = 0.974 δ = 0.07

where

$Y_{lai\ 1}$	=	Bond-air-temperature within LAI 1 plants (°C)
$Y_{lai\ 3}$	=	Bond-air-temperature within LAI 3 plants (°C)
$Y_{lai\ 5}$	=	Bond-air-temperature within LAI 5 plants (°C)
X_1	=	Ambient air temperature (°C)

X_2 = Solar radiation (watt/m^2)

r^2 = Multi-correlation coefficient

δ = Standard error (°C)

Similar measurements and regression analysis have been carried out for the vertical setup. Similar to the regressions generated for the horizontal setup, the difference between the bond air temperature behind the plants and the ambient air temperature is the dependant variable. However, the sparse planting (LAI = 1 & 3) is very sensitive to the low-altitude solar radiation at either early morning or late afternoon. Therefore, no stable foliage air temperature can be achieved behind these plants. Only with very dense plants (LAI= 5), the stable bond air environments obtained at the two orientations are observed to be independent of the low-altitude solar radiation at either early morning or late afternoon. According to the results, multi-regression models are generated for the vertical set-up as follows:

Morning (bond air):

$Y_e = 0.27X_1 + 0.004X_2 + 17.922$ adjusted $r^2 = 0.933$, $\delta = 0.27$

$Y_w = 0.175X_1 + 0.005X_2 + 20.444$ adjusted $r^2 = 0.978$, $\delta = 0.16$

Afternoon (bond air):

$Y_e = X_1 - EXP(0.282X_1 + 0.0003X_2 - 8.903)$ adjusted $r^2 = 0.972$, $\delta = 0.09$

$Y_w = X_1 - EXP(0.312X_1 + 0.001X_2 - 10.655)$ adjusted $r^2 = 0.939$, $\delta = 0.20$

where

Y_e = Bond air temperature behind LAI 5 plants at the eastern orientation, °C)

Y_w = Bond air temperature behind LAI 5 plants at the western orientation, °C)

X_1 = Ambient air temperature (°C)

X_2 = Solar radiation (watt/m^2)

r^2 = Multi-correlation coefficient

δ = Standard error (°C)

The leaf surface temperatures are mostly lower than the corresponding bond-air-temperatures within the foliage. It indicates that the leaves are cooling sources during daytime. Coupled with their outstanding shading effect, the low-temperature leaves are the reason for the lower bond air temperature. Similar regression models have been worked out for estimating the leaf surface temperature.

4. APPLICATION OF THE NEW CONCEPT

The regression models generated for both the horizontal placed plants (e.g. roof top gardens) and the vertically placed plants (e.g. vertical landscaping) form a solid foundation for the calculation of green sol-air temperature. Eventually, the necessary parameters needed to work out a green sol-air temperature are:

- Absorptivity of external surface (it ranges from 0 to 1 depending on the color of hard surface)
- Overall external surface coefficient (it is relevant to is the wind speed and surface roughness)
- Solar radiation (meteorological data)
- Ambient air temperature (meteorological data)
- LAI values (Leaf Area Index).

Green sol-air temperature and sol-air temperature is a pair of inseparable concepts. The most straightforward application is to compare them directly. Although both sol-air temperature and green sol-air temperature are not real temperature derived in reality, they reflect the influences from the sun and outdoor climatic environment over the fluctuation of surface temperatures of building construction. Figure 9 shows the direct comparison. The maximum difference between the sol-air temperatures and the green sol-air temperatures are observed at 1300hr for horizontal surfaces at up to 16.1°C (absorptivity = 0.3). The maximum differences at vertical setup are observed at 0900hr and 1600hr for eastern and western orientations with the maximum difference of around 11.1°C and 11.6°C respectively. With the same LAI value, it seems that plants can contribute more in the reduction of sol-air temperature on the horizontal surface. It is due to the fact that more incoming solar radiation can be intercepted by plants introduced above horizontal surfaces. On the other hand, the sol-air temperature reduction at peak time (early morning or late afternoon) caused by plants at vertical surface is also remarkable. The overall reduction on vertical surfaces is compensated by the minor difference experienced when there is no direct solar radiation received at the orientation. More remarkable reduction can be observed on the hard surface with high absorptivity (see Table 1).

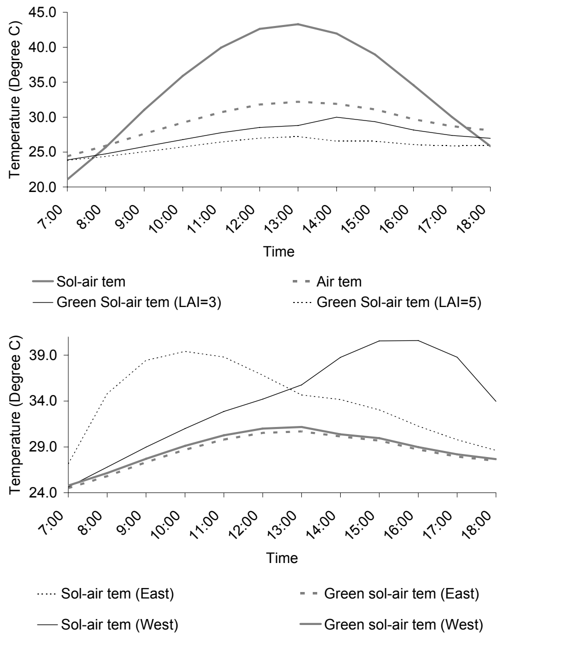

Figure 9: The comparison of sol-air temperature (Sol-air tem) and green sol-air temperature (Green sol-air tem) on 21 March (absorptivity = 0.3. Above: horizontal setup; Below: vertical setup).

Table 1: Summary of average hourly temperature differences between sol-air temperatures and the green sol-air temperatures (absorptivity = 0.9).

	average hourly temperature difference (LAI = 3) on the horizontal surface (°C)	average hourly temperature difference (LAI = 5) on the horizontal surface (°C)	average hourly temperature difference (LAI = 5) at the eastern orientation (°C)	average hourly temperature difference (LAI = 5) at the western orientation (°C)
21 Mar	23.8	26.0	14.7	14.3
22 Jun	20.8	22.9	13.5	13.2
22 Sep	20.9	22.8	12.9	12.5

Another possible application of green sol-air temperature is the estimation of possible heat gain reduction during the daytime. Table 2 shows the cross comparisons of heat gain through bared and planted structures.

Table 2: The possible indoor heat gain caused by horizontally and vertically placed plants during daytime on 21st March (indoor temperature is ranged from 22.5 to 25.5°C).

	Exposed structure	Plants (LAI= 3)	Plants (LAI = 5)
α = 0.3	100%	22-39%	7-27%
α = 0.6	100%	13-25%	4-16%
α = 0.9	100%	11-19%	3-11%

	Exposed structure	Plants at East (LAI=5)	Plants at West (LAI=5)
α = 0.3	100%	36-52%	40-55%
α = 0.6	100%	23-37%	26-39%
α = 0.9	100%	17-28%	19-31%

The green sol-air temperature may also have influence on existing building regulations. Table 3 shows the possible contribution of plants on increasing Envelope Thermal Transfer Value for Buildings (ETTV) values [6].

Table 3: The possible contribution of plants on increasing ETTV values for roof, East-facing wall and West-facing wall.

Green coverage on roof	Increase of ETTV by plants (LAI=3)	Increase of ETTV by plants (LAI=5)
10%	1.06 x ETTV	1.07 x ETTV
20%	1.12 x ETTV	1.15 x ETTV
30%	1.20 x ETTV	1.25 x ETTV
40%	1.28 x ETTV	1.37 x ETTV
50%	1.38 x ETTV	1.50 x ETTV
60%	1.49 x ETTV	1.67 x ETTV
70%	1.63 x ETTV	1.88 x ETTV
80%	1.79 x ETTV	2.16 x ETTV
90%	1.98 x ETTV	2.52 x ETTV
100%	2.22 x ETTV	3.03 x ETTV

Green coverage on wall	Increase of ETTV by plants (LAI=5) at East-facing wall	Increase of ETTV by plants (LAI=5) at West-facing wall
10%	1.05 x ETTV(East)	1.04 x ETTV(West)
20%	1.10 x ETTV(East)	1.09 x ETTV(West)
30%	1.16 x ETTV(East)	1.15 x ETTV(West)
40%	1.23 x ETTV(East)	1.21 x ETTV(West)
50%	1.31 x ETTV(East)	1.27 x ETTV(West)
60%	1.39 x ETTV(East)	1.35 x ETTV(West)
70%	1.49 x ETTV(East)	1.43 x ETTV(West)
80%	1.60 x ETTV(East)	1.52 x ETTV(West)
90%	1.73 x ETTV(East)	1.63 x ETTV(West)
100%	1.89 x ETTV(East)	1.75 x ETTV(West)

5. CONCLUSION

Green sol-air temperature is a simplified calculation method for predicting thermal benefits of plants around buildings. Based on the existing sol-air temperature concept and the empirical data generated from the green experiment, the method helps to translate plants' intervention over urban climate and buildings into quantitative data at micro level. Firstly, the impacts of greenery have been strictly link to their corresponding LAI values through the experiment. It indicates that the LAI value is the critical parameter which governs the possible impact of plants around buildings. This applies to not only horizontal surfaces (roofs) but also vertical surfaces (facades). With large LAI values, more solar radiation can be intercepted and a stable bond air environment can be formed within the foliage. The quantitative data are not limited to describe the critical role of LAI values. The regressions have been generated from only the foliage which can create a relatively stable bond-air condition. According to the experiment, the LAI benchmark for achieving a stable bond air temperature within foliage should be more than 3 on a horizontal surface and more than 5 at the western and the eastern orientations. The regression models basically represent the abilities of plants on mediating the micro climate with focus on reducing ambient air temperature and solar radiation during the daytime. Green sol-air temperature is calculated based on the regressions and given LAI values. The potential applications of green sol-air temperature can be reflected at the direct comparison with sol-air temperature, the possible reduction of heat gain, the possible increase of the current ETTV value, and so forth.

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